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RESEARCH FOR IMPROVED SUBSONIC AND SUPERSONIC RAIN EROSION RESISTANT MATERIALS

GEORGE F. SCHMITT, JR.

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FOREWORD

This report was prepared by the Elastomers and Coatings Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, under Project No. 7340, "Nonmetallic and Composite Materials," Task No. 734007, "Coatings for Energy Utilization, Control, and Protective Functions." The work was conducted with George F. Schmitt, Jr. acting as Project Engineer.

This report covers a period from 1 May 1964 to 30 April 1966.

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This technical report has been reviewed and is approved.

W. P. JOHNSON, Acting Chief
Elastomers and Coatings Branch
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ABSTRACT

Investigations of advanced coatings materials performed on a whirling-arm rain erosion simulation device at 500 mph have led to new protective coatings which are capable of providing protection against damage from rain droplet impingement at subsonic velocities. Polyurethane coatings were determined to be the most erosion resistant of the elastomeric-polymeric materials currently available. These polyurethanes are a considerable improvement over the specification neoprene erosion coating. Plasma-sprayed ceramic coatings of alumina and alumina/titania are potentially applicable for supersonic erosion protection where dielectric properties must be maintained. Electroplated nickel coatings directly applied to plastic laminates will provide several orders of magnitude improvement in erosion resistance over conventional elastomeric coatings.

(This abstract may be further distributed by any holder only with specific prior approval of the Elastomers and Coatings Branch (MANE) Nonmetallic Materials Division, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433.)

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SECTION I

INTRODUCTION

The investigation of the phenomenon known as rain erosion, that is, materials damage caused by the impingement of rain droplets at high speeds, has long been a concern of the United States Air Force. The Air Force Materials Laboratory at Wright-Patterson Air Force Base has conducted and sponsored rain erosion research since 1947 when such erosion was first observed on aircraft flying at speeds of 400 MPH and above.

Past research on rain erosion has been principally concerned with mechanism studies which were conducted by Engel (Reference 1), materials research by Wahl and others (Reference 2), and laboratory simulation techniques by Beal and Wahl (Reference 3). These investigations were continued at a high level of effort until 1957 when they were considerably reduced.

With the ever-increasing use of fighter aircraft that fly supersonically and missiles that operate in a supersonic regime or are carried externally on high speed aircraft and repeatedly exposed, the "rain erosion" of the nose sections and leading edges on these systems became a major concern for their efficient all-weather operation. By 1964 the pressing problems introduced by these increased supersonic and high subsonic speed flights and the severe rain erosion damage at these velocities necessitated reactivating research and experimentation in this area. Such work is currently being pursued at an accelerated rate of effort by the Air Force Materials Laboratory.

An excellent state-of-the-art survey summarizing investigations in rain erosion over the past twenty years has been published (Reference 4). This report contains a comprehensive bibliography of rain erosion publications during this period and serves as a basis for much of the work currently being conducted.

The work reported includes investigation of improved materials for subsonic and possibly supersonic rain erosion resistance by use of a whirling-arm simulation device. The purpose is to provide a better insight into the phenomenon of rain erosion, an investigation of promising materials and resultant damage caused by water droplet impact, and information on which to base future contractual and in-house research.

SECTION II

PHENOMENON OF RAIN EROSION

Resistance to erosion by water drops is more than simply impact or abrasion resistance. The pheuomenon is characterized by two distinct actions. The first is the impact of the drop striking the aircraft or missile; at high speeds this is like a solid particle hitting the system. The second is a radial flow of water as the drop fragments. This rush of water in a radial direction is at a velocity approximately three to four times that of the impact velocity and sets up high shear stresses in the coating or surface material.

There are almost as many suggested mechanisms of erosion failure as there are classes of materials (Reference 1). Thin resilient coatings such as neoprenes or polyurethanes will transmit the shear stress to the substrate causing a failure in the adhesive bond. Additional impacts on this same area cause the coating to stretch or deform, "bubble" and then burst under repeated impingement.

Plastic type materials and soft metals flow plastically under the compressive stress of the water impact resulting in cratering and pitting. The pits or craters grow in size until rapid erosion occurs.

Plastic laminated materials will fail by eroding away of the upper layers of fabric resulting in holes in the surface. This erosion is often rapid enough to cause structural failure of the entire component.

Another form of failure is that associated with materials which do not deform under impact loads, such as ceramics and high hardness metals. These impacts cause small imperfections in the surface to be removed with subsequent work hardening and fracture in the pits formed. As these imperfections are removed, protrusions are formed against which the flowing liquid acts to exert a shear stress and a turning moment. Once again failure of the coating or surface may result.

The mechanisms described above operate at subsonic speeds and are sure to be compounded at supersonic velocities.

SECTION III

REQUIREMENTS FOR RAIN EROSION RESISTANT MATERIALS

The needs for protective materials to resist the impacts and shear stresses of rain drops actually fall into two broad classes; i.e., subsonic protection and supersonic protection. The subsonic regime is of interest because of applications for aircraft and helicopter blades which may be exposed to rain environments at high subsonic speeds. Supersonic exposure may be experienced on advanced supersonic aircraft and missiles where penetration of rain clouds may be necessary and desirable for tactical and evasive purposes.

SUBSONIC RAIN EROSION RESISTANT COATINGS

Protection of subsonic aircraft and helicopter rotor blades is currently accomplished by neoprene coatings (sprayed, brushed, or prefabricated boots) applied to leading edges and radomes. This material has been in use for over 10 years and, while it does afford some protection, it has severe limitations. At speeds greater than 500 MPH, the temperature limitations (max 200°F) become a problem; the neoprene coating also will not withstand the more severe impacts and shear stresses at these higher speeds. Another limitation is its poor weathering characteristics when exposed to ultraviolet light and ozone.

Extreme care must be taken during application of the neoprene to obtain a smooth surface since its erosion resistance is highly sensitive to the coating process.

The need for an improved elastomeric coating to protect reinforced plastic radomes, helicopter blades, etc. from subsonic rain impacts is wide-spread and vital. A nonmetallic coating is needed for protection of radomes because of the incompatibility of metals with radar (both offensively and defensively). If an elastomeric material can be found to withstand the shear and impact stresses on the surface exposed to the rain and still retain enough integrity to prevent this stress from destroying the adhesive bond, protection can be afforded the structural component coated with this material.

Another area of concern for coatings which possess subsonic erosion resistance is the high temperatures supersonic aircraft and missiles may experience in flight, although not necessarily in rain. These may reach 400°F at Mach 2 and 650°F at Mach 3, which are beyond the capability of most available elastomeric coatings. New subsonic protective coatings must retain their resistance after the high temperature exposure.

SUPERSONIC RAIN EROSION RESISTANT COATINGS

Pilots are presently instructed to avoid rain at supersonic speeds. However, for low level aircraft dash missions and high speed missiles, it is necessary to be able to penetrate rainstorms supersonically since avoidance is often impossible or even undesirable. Unprotected parts of aircraft and missiles such as radomes in this type of exposure will be destroyed in a matter of seconds. To overcome this problem, ceramic caps or all-ceramic radomes are currently used on a limited basis in lieu of plastic radomes. However, these are limited because of inherent brittleness, matching problems and structural weaknesses of the ceramics.

It has been shown that in order to obtain sufficient erosion resistance, a ceramic must be applied in a highly dense form. Again the use of metals for this purpose is prohibited because of radar transmission requirements. In 1960 Engel (Reference 5), and earlier, Wahl and co-workers (Reference 6) at Cornell, presented theoretical and experimental data leading to the conclusion that both hot pressed aluminum oxide and white sapphire (single crystal alpha alumina) are essentially not eroded by 2 mm water drops at speeds up to Mach 10.

The supersonic high performance tactical missile regime presents still another difficulty which cannot be avoided and that is the problem of extremes of erosion and elevated temperature. The ceramics will certainly withstand temperatures up to 1200°F in air but developing a plastic laminate which will withstand such temperatures is another problem. The areas of thermal matching of the protective ceramic coating with the plastic substrate, as well as thermal shock and adhesion, drastically complicate the situation. Times at temperature generally decrease as velocity increases.

An area in which use of metals is permissible, would be exposed structural components of advanced systems where radar compatibility is not a prime requirement. This would also apply in very high speed turbines and compressors, now being designed, in which damage to blades from water drops and dust particles is of concern

ANTICIPATED FUTURE REQUIREMENTS

Based on projected flight profiles of advanced systems (References 7 and 8), the following requirements for rain erosion protection can be projected. (See Figures 1, 2 and 3.) A typical Mach 3 military aircraft on a 2 1/2 hour mission has the possibility of encountering rain of 0.1-0.3 inches/hour at Mach 0.9 for 50 minutes and rain of up to 2.0 inches/hour at Mach 1.2 for as much as 30 minutes. (See Figure 11.) Although the probability of its being in the rain for all this time is very low, if it is exposed to rain 10 percent of the mission, this would represent a significant amount of rain exposure. When this is projected over the service life of the aircraft, the requirement appears to be sufficient resistance to withstand rainfall of 2.0 inches/hour at Mach 1.5 for one hour. Fortunately the flight speeds above Mach 2 are at altitudes where rain is insignificant; however, the temperature cycling problem is still pertinent.

The needs for a Mach 2.2 supersonic transport are not quite as severe but still require an improvement in the state-of-the-art. A supersonic transport of this type on a run from London to New York which would consume about 192 minutes has the possibility of experiencing 32 minutes at Mach 0.9 in rainfall ranging from 0.2 to 1.9 inches/hour. Again the probability exists of encountering rain for only a small fraction of the flight time. Assuming a 30,000 flight hour life of the aircraft, the amount of possible and probable rain exposure becomes large.

The Mach 3 supersonic transport will experience a limited amount of rain because of its flight profile. Upon a typical departure from JFK International Airport it might experience 10 minutes in rain of 0.1 to 2.0 inches/hour. Upon arrival at the same airport from across the Atlantic it might undergo 11-15 minutes in 0.1 to 1.25 inches/hour rainfall. Here again a 30,000 flight hour life would require rain erosion resistance of at least an hour at Mach 1. As mentioned before, the thermal cycling environment of 650°F for Mach 3 is a major consideration. See Table I for a summary of anticipated rain erosion requirements.

With the above requirements becoming increasingly vital, this AFML investigation was undertaken to provide a basis for decision-making and direction of future coatings research to overcome the rain erosion problem.

SECTION IV

LABORATORY EQUIPMENT

Subsonic rain erosion investigations were conducted on an apparatus located in Building 20A at Wright-Patterson Air Force Base, Ohio. This equipment consisted of a 6-foot diameter propeller blade made of tempered boiler plate mounted vertically on a 100 horsepower electric motor. At 2400 RPM it was capable of attaining speeds of 500 miles per hour at the blade tip. (This equipment was disassembled and removed at the conclusion of the research reported herein to be replaced by a supersonic whirling-arm rig.)

The speed of the equipment was regulated by a resistor bank from which rigid control was possible. A revolution counter was utilized for monitoring velocity along with vibration pickups for gauging specimen balance and smooth operation. The specimens were observed during operation by use of a mirror and periscope arrangement and a stroboscopic unit synchronized with the blade revolutions. This system enabled the observer to note the time of coating failure; i.e., penetration to the substrate or loss of adhesion.

The water system used to simulate the rain environment consisted of a 6-foot diameter circle of 2-inch pipe equipped with twelve equally spaced hypodermic needles to yield a rainfall simulation of from 2 to 24 inches per hour. The hypodermic needles were 18-gauge (1.245 mm ID) which produce rain droplets of 1.5-2.0 mm diameter as determined photographically. The water system operated with 35 psig in the spray ring; this pressure enabled a stream of waterdrops to impinge on the material specimens (which were inserted in the blade tip) without distortion when running.

The whirling-arm apparatus is shown in Figures 4-8.

The specimen configurations were of several types: 1/8-inch leading edge aluminum, 3/32-inch leading edge laminate specimens, and conformal specimens of aluminum or various laminated materials. (See Figures 9, 10, and 11 for these configurations.) The conformal specimens were employed extensively since they were easy to coat and their low drag and light weight enabled efficient operation of the apparatus.

SECTION V

VARIABLES STUDIES

The simulation of the rain environment which an aircraft flying at subsonic velocities would encounter, is a very difficult experimental task. The use of a whirling-arm device enables attainment of velocity, and the water system described provides repeated water impacts which are necessary for true simulation. The other variables which must be considered in designing an evaluation technique for rain erosion resistance are numerous and difficult to correlate. Among these are velocity of test specimen, rainfall intensity, rain droplet size and shape, configuration of leading edge upon which the material is applied, deciding when a material has failed, isolating erosion failures from adhesive failures, etc.

A number of studies have been conducted on the 500 MPH equipment and are described below:

MEASUREMENT OF DROP SIZE AND SHAPE

A unique method of measuring drop size and shape has been developed by Mr. Harold A. Schuetz of the Air Force Aero Propulsion Laboratory. In this technique a stroboscopic unit is focused on the water stream from a hypodermic syringe. The firing time of the unit is adjusted so that the individual droplets may be seen.

The water stream is positioned in front of a Plexiglass sheet on which a 1 by 1 cm grid has been scribed. A Polaroid camera is adjusted so that the strobe unit will flash enough times in its shutter time to permit taking of photographs.

A series of runs was made with different sizes of needles (15, 18, 19, 20, 22, 23 and 26-gauge) at varying line pressures (2.5, 5, 10, 15 and 20 PSIG). See Table II. The droplet size was highly dependent on needle gauge and somewhat dependent on line pressure. A sample of photographs taken is shown in Figure 12-15 which illustrates the effect of needle size and line pressure on droplet configuration.

EFFECT OF RAINFALL RATE, DROP SIZE, AND VELOCITY

A study of the effect of rainfall rate, drop size, and velocity on the erosion characteristics of various materials was conducted. Two basic materials were chosen: a specification black neoprene coating and a polyurethane boot. These were applied to the 1/8-inch leading edge aluminum specimens for evaluation.

Runs were made at several speeds (300, 400, 450 and 500 MPH) in four to eight inches per hour of simulated rain with drop sizes of 2.5 mm diameter (15-gauge needle), 1.8 mm diameter (18-gauge needle), and 0.4 mm diameter (22-gauge needle). The results of these evaluations are shown in Table III and Figures 16-18. As expected, erosion was more severe with increasing speed and failure times were considerably faster in the heavier rainfall. The larger drops also promoted an increased rate of erosion.

The erosion resistance of the urethane system was approximately twice that of the neoprene. However, it should be pointed out that the thickness of the urethane coating was also approximately three times that of the neoprene. Other urethanes investigated have exhibited resistance three to four times that of the specification neoprene material at similar thicknesses of the two materials (See Figure 19).

Additional specimens of the neoprene coating at varying thicknesses on the conformal aluminum specimens prepared by brushing or dip-coating were also evaluated at 500 MPH in 2 inches/hour rainfall as a base line. The results of this investigation are summarized in Table IV. Once again the erosion rate was directly a function of rainfall rate, drop size, and velocity.

SECTION VI

MATERIALS INVESTIGATION

The investigation of numerous materials for their rain erosion resistance was concentrated on several classes of coatings and structural materials. The classes of materials included polymeric-elastomeric materials, ceramics, metals, and reinforced plastic laminates. The emphasis has been on nonmetallic materials since protection of electromagnetic windows which require a nonmetallic surface is of prime concern. However, for aircraft leading edges and coatings on turbine and compressor blades of engines, the use of metals is pertinent.

The examinations of materials were initially conducted by applying coatings on the 1/8-inch leading edge aluminum specimens (See Figure 9) and the 3/32-inch leading edge laminate specimens (See Figure 10); these specimens were then exposed to a simulated rain environment of 24 or 12 inches/hour rainfall at 500 MPH. The rainfall rate was later reduced to 2 inches/hour to more nearly correspond with what might actually be experienced in a practical case. The specimen holder on the whirling-arm was later adapted to accommodate the conformal aluminum and laminate specimens (See Figure 11), which are identical in configuration to the specimens previously employed at Cornell Aeronautical Laboratory from 1950 to 1959 (Reference 2). The rain erosion protective coatings specifications (Mil-C-7439B and C-27315) were developed using this specimen shape (References 9 and 10). The only change necessary was to use a specimen 2.5 inches long rather than 5 inches long.

All evaluations were conducted at 500 miles per hour with most being conducted in 2 inches/hour simulated rainfall.

ELASTOMERS-POLYMERS

The polymeric-elastomeric materials evaluated on the 1/8-inch leading edge radius specimens indicated that polyurethane elastomers were the most promising for protection from rain. Other elastomers and/or polymers investigated included:

fluorosilicones
dimethyl silicones
silicone sealants and rubbers
carborane-silicone copolymer
polyimides (2 kinds)
phenoxy polymers (3 kinds)
poly-paraxylylene
ionomer films (2 kinds)
urethane tapes
black neoprene
white neoprene
neoprene over Kel-F
paint-on urethanes (5 kinds)
elastomeric urethanes (6 kinds)

The evaluations of these materials on the 1/8-inch leading edge radius aluminum and 3/32-inch leading edge radius laminates are summarized in Tables V and VI respectively.

Since the adaptation of the whirling arm to utilize the conformal specimen configuration, additional elastomeric type materials have been examined on aluminum and reinforced laminates. These include:

polycarbonate sheet
neoprene boots with gum rubber
and/or Dacron cloth backing

sprayed neoprene
cork sheet
abrasive tapes (5 kinds)
Teflon sheet
unfilled urethanes
fluidized-bed epoxy
fluidized-bed silicone-epoxy
Plexiglas sheet
Nitroso polymer formulations (2 kinds)

These results are included in Tables VII and VIII.

The evaluations of all elastomeric materials have indicated that polyurethanes exhibit superior erosion resistance compared to other elastomers as materials per se. However, when they are applied as coatings or as sheets bonded on the substrates, difficulties with adhesion, cold flow of the urethane films, and structural failure by chipping away of the coating are experienced. The neoprene material on the other hand, erodes more rapidly and uniformly by a gradual wearing-away of the surface. Of the other elastomers examined, most exhibited inferior resistance to the rain impacts with some (ionomers, glass resins, Teflon) failing because of brittleness. It should be noted that none of these materials, or the urethanes, for that matter, were formulated or developed specifically for rain erosion protection. Therefore, failures in rain should by no means be construed as indicating inferiority of these materials for other applications.

CERAMICS

The need for nonmetallic materials which withstand supersonic rain impact has prompted the evaluation of numerous ceramic materials. A number of materials were evaluated including alumina, silica, titania and zirconia. These were generally examined as thin coatings (0.030-in. or less) over plastic laminates or aluminum substrates.

Since the ceramics must be in a highly dense form to possess sufficient rain erosion resistance, methods of depositing dense coatings were investigated. Among the techniques examined were flame spraying, plasma spraying, high solids film casting, spraying on a male mold and then bonding the coating to the laminate, or spraying on a mold and then laying up a laminate on the inside.

The substrates on which the ceramics were evaluated included 1/32-inch leading edge radius aluminum, 1/8-inch leading edge radius aluminum, conformal aluminum specimens, and PBI and polyester laminates with a 3/32-inch leading edge radius.

Of the methods of application examined, plasma-spraying produced ceramic coatings with the highest level of resistance. The flame-sprayed coatings also resisted the rain but not as well.

A principal difficulty anticipated and experienced was that of coating-metal or coating-laminate interfacial adhesion. In many instances the failure of the material under the influence of rain impact was a bond failure rather than erosion or brittle fracture. Several surface preparation techniques were employed to improve this interfacial adhesion such as grit blasting, porcelain enamel primers, and special adhesives with only limited success.

Despite the difficulties and shortcomings of the ceramic materials examined, it is believed that this class of materials offers the best hope for erosion resistant nonmetallic coatings capable of providing protection at supersonic velocities in the rain environment.

The evaluation of the ceramics applied by various techniques on the aluminum substrates are summarized in Table IX while those of ceramics on plastic laminates are included in Table X.

METALS

Metals are necessary for leading edge surfaces, helicopter rotor blades, compressor blade surfaces, and other structural components of aircraft, and must be considered for the possible damage they may suffer when exposed to rain. A number of metallic surfaces have been exposed to the rain environment for varying periods and the soft metals, for examples, aluminum, flow plastically upon repeated impact with cratering and pit formation. Hard metals such as stainless steel, titanium, and nickel, withstand the impact and shear forces for extended periods in rain.

Several techniques for obtaining thin metal coatings, for example electroplating and plasma spraying of metal mixtures, have also been examined. Plastic reinforced laminates coated with electroplated metals have been prepared for this study by Mr. James H. Weaver of the Elastomers and Coatings Branch, Air Force Materials Laboratory (Reference 11). These plated metals, particularly nickel, have exhibited outstanding resistance to rain erosion on metallic and plastic laminate substrates. It is believed that the use of electroplated metals may be an improvement in the state-of-the-art for rain protection where metal surfaces are allowable.

The results of metal surface investigations are presented in Table XI.

For a relative ranking of the resistance of various classes of materials, see Figure 20.

SECTION VII

DISCUSSION

The superior performance of the polyurethane materials in resisting the subsonic rain environment may be attributed to several factors. The urethanes are tougher than many other elastomers and simply have sufficient strength (impact, tensile, abrasion resistance) to withstand the rain impact.

The neoprene material performs relatively well in rain because of its resiliency and ability to recover between successive impacts. Although the polyurethanes are not as resilient in general, as the neoprene, a material based on urethanes but designed specifically for resistance to rain damage will lead to an improved erosion protective coating. A research program with that specific goal is now being conducted under Air Force sponsorship. This effort will study the chemical structure, physical properties, and rain erosion resistance of urethanes, and will develop a substantially superior subsonic rain-resistant coating.

The high density ceramics needed for supersonic rain erosion protection are desirable as thin coatings because of weight reduction and efficient electromagnetic design considerations. With this in mind, the bulk densities required for erosion resistance are difficult to obtain in a 30 mil coating (an upper limit for design purposes).

Of the methods currently available for depositing inorganic oxide ceramics with reasonable control over density as a function of process conditions and a relatively high deposition rate, plasma spraying appears to offer the most promise for obtaining and controlling the thin dense ceramic surfaces. Other techniques include flame spraying, vacuum evaporation, sputtering, and chemical vapor deposition. However, on the basis of evaluations conducted in this program, the plasma spraying should yield supersonic protective coatings.

Based on the above considerations, the Air Force is sponsoring a research effort to investigate plasma-spraying and chemical vapor deposition and their process variables as a route to obtaining thin, dense, adherent ceramic coatings.

It is readily apparent that the subsonic and supersonic rain environments present a difficult challenge for protective coatings. Progress is being made with hopes for new and improved protective coatings for both regimes.

The plating of nickel coatings on plastic laminates for rain erosion resistance is one of the significant improvements to arise from this investigation. The nickel withstands the rain impacts for long periods of time with no erosion evident, if care is taken to obtain good adhesion to the plastic substrate. Unfortunately the electromagnetic requirements for radomes, which necessitate the use of nonmetallic materials, preclude protection of these surfaces with the electrodeposited nickel. It is expected that the use of these plated coatings will provide substantial improvements in protection of plastic leading edges for aircraft and compressor blades, rotor blades, and other structural applications.

The failure times on the whirling-arm facility at Wright-Patterson Air Force Base are considerably faster than those obtained on other whirling-arm equipment. This may be attributed to the nature of the water injection system in which a small stream of water droplets must be propelled horizontally at a reasonably high pressure in order to reach the specimens while rotating and mounted on the vertical blade tip. The multiple water drop impacts per revolution with this technique actually simulates a much higher rainfall intensity than the nominal rate based on water flow measurements and area exposed. Further, the relaxation and recovery times for elastomers passing intermittently through the water streams from the needles may be such as to prolong the life of these materials in the rain environment.

The results indicated for various materials do give a relative ranking of their rain erosion resistance similar to those obtained on other whirling-arm devices even though orders of magnitude are different.

SECTION VIII

CONCLUSIONS

1. Of the elastomeric-polymeric materials currently available, the polyurethanes withstand subsonic rain damage best.

2. The rain erosion resistance of the polyurethanes is thickness-dependent up to 15 mils, (this is also true for specification neoprene and other materials at varying thicknesses).

3. Coatings of improved polyurethanes designed specifically for rain erosion resistance, should offer substantially improved protection against rain impact and shear forces at subsonic velocities when compared with the difficult-to-apply neoprene.

4. Dense oxide ceramics offer the best hope for nonmetallic supersonic erosion resistant materials.

5. Plasma-spraying of ceramics is a deposition process with considerable promise for obtaining thin, dense, and adherent coatings.

6. Electroplated nickel over plastic reinforced laminates offers several orders of magnitude improvement over conventional elastomeric or even ceramic rain erosion protective coatings. The application of plated coatings is limited to instances where electromagnetic considerations do not dictate a nonmetallic coating.

SECTION IX

FUTURE WORK

1. The Air Force Materials Laboratory's whirling-arm capability has been completely redesigned and a new apparatus capable of variable speeds to Mach 1.2 will be constructed. This equipment will utilize an 8-foot 4340 steel, double-arm blade operating in a horizontal position and powered by a 400 HP motor. Other features will include an improved rain simulation system and an optical viewing system utilizing closed circuit television.

2. Use of the above equipment when completed will enable increased emphasis on ceramic materials for supersonic protection. Evaluations can be conducted supersonically where they have been made at 500 MPH in the past for lack of a supersonic capability.

3. Several materials systems will be examined, including oxide ceramics and plated materials applied over elastomeric coatings, to give a hard surface and a "bumper" effect.

4. Additional research in the protection of plastics by plated metals will be conducted. This will be extended to sand erosion resistance investigations in an attempt to utilize its protective ability for helicopter rotor blade and aircraft engine compressor blade applications.

5. Correlations will be made between actual flight tests, such as the Rough Rider series, and experimental results obtained on the whirling arm. Other promising materials will be flight tested, where possible.

6. The evaluation of promising new materials for subsonic and supersonic applications will continue as before.

SECTION X

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TABLE I

SUMMARY OF RAIN EROSION REQUIREMENTS

System	Time at Speed in Rain	Maximum Temperature
Present tactical support aircraft	30 min @500 mph	200°F
Improved tactical support aircraft	30 min up to Mach 2.0 (low level)	450°F
Mach 3.0 military	120 min @Mach 0.9 + 60 min @Mach 1.5	650°F
Mach 2.2 SST	300 min @Mach 0.9	500°F
Mach 3.0 SST	60 min @Mach 1.0	650°F
High performance missile (to Mach 5.0)	up to 30 sec; up to Mach 5.0	2000°F

TABLE II

SIZES OF WATER DROPS FROM HYPODERMIC SYRINGES AT VARYING LINE PRESSURE

Gauge No.*	Inside Diameter of Needle, mm	Line Pressure, PSIG	Average Size of Drop, mm
15	1.829	2.5	3.0
		5.0	2.8
		10.0	2.5
		15.0	2.5
		20.0	2.5
18	1.245	2.5	2.0
		5.0	1.8
		10.0	1.8
		15.0	1.8
		20.0	1.6
19	1.067	2.5	1.3
		5.0	1.1
		10.0	0.9
		15.0	0.85
		20.0	0.8
20	0.889	2.5	0.8
		5.0	0.8
		10.0	0.7
		15.0	0.6
		20.0	0.6
22	0.711	2.5	0.5
		5.0	0.4
		10.0	0.4
		15.0	0.3
		20.0	0.3
23	0.635	2.5	0.2
		5.0	0.2
		10.0	0.15
		15.0	0.15
		20.0	0.15
26	0.457	5.0	0.3
		10.0	0.15
		15.0	0.1
		20.0	0.1

*Corresponds to Birmingham Wire Gauge

TABLE III

EROSION TIMES AS A FUNCTION OF VELOCITY, DROP SIZE, AND RAINFALL RATE

Specimen No.[1]	Velocity (mph)	Droplet Diameter (mm)	Rainfall Rate (inches/hour)	Time to Failure (sec)	Comments
V-1	300	2.5	4	600.0	No erosion
V-3	300	2.5	4	568.8	No erosion
V-5	400	2.5	4	158.6	Erosion failure[2]
V-7	400	2.5	4	142.2	Erosion failure
V-9	450	2.5	4	39.2	Erosion failure
V-11	450	2.5	4	23.4	Erosion failure
V-13	500	2.5	4	18.6	Erosion failure
V-15	500	2.5	4	33.4	Erosion failure
V-17	300	1.8	4	252.4	Erosion failure
V-19	300	1.8	4	1200.0	No erosion
V-21	400	1.8	4	300.0	Erosion failure
V-23	400	1.8	4	300.0	Slight erosion
V-25	450	1.8	4	64.2	Erosion failure
V-27	450	1.8	4	90.2	Pinhole failure
V-29	500	1.8	4	135.6	Erosion failure
V-31	500	1.8	4	79.6	Erosion failure
V-33	300	0.4	4	600.0	No erosion
V-35	300	0.4	4	600.0	No erosion
V-37	400	0.4	4	600.0	No erosion
V-39	400	0.4	4	600.0	No erosion
V-41	450	0.4	4	600.0	Pinhole erosion
V-43	450	0.4	4	600.0	Slight erosion
V-45	500	0.4	4	387.6	Erosion failure
V-47	500	0.4	4	405.6	Erosion failure
V-49	300	2.5	8	600.0	Slight erosion
V-51	300	2.5	8	600.0	Slight erosion
V-53	400	2.5	8	33.2	Erosion failure
V-55	400	2.5	8	74.0	Erosion failure
V-57	450	2.5	8	34.6	Erosion failure
V-59	450	2.5	8	107.4	Erosion failure
V-61	500	2.5	8	26.8	Erosion failure

TABLE III (CONTD)

Specimen[1] No.	Velocity (mph)	Droplet Diameter (mm)	Rainfall Rate (inches/hour)	Time to Failure (sec)	Comments
V-63	500	2.5	8	11.2	Erosion failure
V-65	300	1.8	8	1200.0	No erosion
V-67	300	1.8	8	713.0	Pinhole erosion
V-69	400	1.8	8	150.2	Erosion failure
V-71	400	1.8	8	115.4	Erosion failure
V-73	450	1.8	8	29.0	Erosion failure
V-75	450	1.8	8	137.4	Erosion failure
V-77	500	1.8	8	58.0	Erosion failure
V-79	500	1.8	8	76.6	Erosion failure
V-81	300	0.4	8	600.0	No erosion
V-83	300	0.4	8	600.0	No erosion
V-85	400	0.4	8	600.0	Slight erosion
V-87	400	0.4	8	600.0	Slight erosion
V-89	450	0.4	8	405.2	Erosion failure
V-91	450	0.4	8	364.2	Erosion failure
V-93	500	0.4	8	188.6	Erosion failure
V-95	500	0.4	8	203.8	Erosion failure
V-97	300	2.5	4	600.0	No erosion
V-99	500	2.5	4	16.4	Erosion failure
V-101	300	1.8	4	1200.0	No erosion
V-103	500	1.8	4	191.0	Erosion failure
V-105	300	0.4	4	600.0	No erosion
V-107	500	0.4	4	900.0	No erosion
V-109	300	2.5	8	600.0	No erosion
V-111	500	2.5	8	21.2	Erosion & adhesion failure

TABLE III (CONTD)

Specimen[1] No.	Velocity (mph)	Droplet Diameter (mm)	Rainfall Rate (inches/hour)	Time to Failure (sec)	Comments
V-113	300	1.8	8	600.0	No erosion
V-115	500	1.8	8	231.6	Erosion failure
V-117	300	0.4	8	600.0	No erosion
V-119	500	0.4	8	483.4	Severe erosion

Notes: All substrates are 1/8 in. leading edge radius 2024 aluminum.
Specimens V-1 through V-95 are 11-12 mils Goodyear 23-56 black neoprene per Mil-C-7439B.
Specimens V-97 through V-107 are 22 mils Goodrich black Estane urethane.
Specimens V-109 through V-119 are 22 mils Goodrich yellow Estane urethane.

1. Specimen numbers actually represent two materials specimens which were evaluated at the same time on the whirling arm.

2. A failure of the coating is that moment when it is penetrated to the aluminum substrate.

TABLE IV

EVALUATION[1] OF SPECIFICATION NEOPRENE[2] AT VARYING THICKNESSES ON ALUMINUM SUBSTRATES[3]

Specimen[4] No.	Number of Coats	Application Method	Coating Thickness (mils)	Time to Failure (sec)	Comments
C-5	3	Brush	9-12	318.0	Erosion failure[5]
C-7	3	Brush	9-12	314.4	Erosion failure
C-9	3	Brush	9-12	387.8	Erosion failure
C-11	6	Brush	17-20	359.6	Erosion failure
C-13	6	Brush	17-20	489.4	Erosion failure
C-15	6	Brush	17-20	288.0	Erosion failure
C-17	2	Dip	10-13	181.8	Erosion failure
C-19	2	Dip	10-13	135.0	Erosion failure
C-21	2	Dip	10-13	153.2	Erosion failure
C-23	4	Dip	16-19	244.6	Erosion failure
C-25	4	Dip	16-19	343.2	Erosion failure
C-27	4	Dip	16-19	189.4	Erosion failure

1. All evaluations were conducted at 500 mph in 2 inches/hour simulated rainfall.
2. Goodyear 23-56 neoprene per Mil-C-7439B.
3. All substrates are conformal leading edge 2024 aluminum.
4. Specimen numbers represent two identical specimens which were evaluated together.
5. Erosion failure is a penetration of the coating to the substrate without loss of adhesion.

TABLE V

EXPOSURE TIMES FOR ELASTOMERIC-POLYMERIC MATERIALS ON 1/8"L. E. ALUMINUM SPECIMENS

Specimen[1] No.	Material	Primer or Adhesive	Coating Thickness (mils)	Rainfall (inches/hour)	Time to[2] Failure (sec)	Type of Failure
22-23	Specification neoprene (A)	Bostik 1007	20	24	43.0	Erosion
24-25	Specification neoprene (A)	Bostik 1007	20	24	47.0	Erosion
67-68	Spec. white neoprene (A)	Bostik 1007	20	24	23.7	Erosion
69-70	Spec. white neoprene (A)	Bostik 1007	20	24	26.2	Erosion
71-72	Specification neoprene (B)	Bostik 1007	20	24	14.2	Erosion
73-74	Specification neoprene (B)	Bostik 1007	20	24	16.4	Erosion
51-52	Fluorosilicone	RTV silicone	10	24	45.6	Erosion
53-54	Fluorosilicone	RTV silicone	20	24	33.2	Erosion
55-56	Dimethylsilicone	RTV silicone	10	24	16.8	Erosion
57-58	Dimethylsilicone	RTV silicone	20	24	19.0	Erosion
115	Dimethylsilicone	RTV silicone	22	24	17.8	Erosion
116	Dimethylsilicone	RTV silicone	22	24	14.4	Erosion
59-60	Dimethylsilicone gum	RTV silicone	10	24	15.2	Erosion
61-62	Dimethylsilicone gum	RTV silicone	20	24	26.6	Erosion
113	Dimethylsilicone gum	RTV silicone	20	24	17.5	Erosion
114	Dimethylsilicone gum	RTV silicone	20	24	24.2	Erosion
63-64	Silicone	RTV silicone	10	24	17.3	Erosion
65-66	Silicone	RTV silicone	20	24	16.2	Erosion
111	Silicone sealant	RTV silicone	30	24	38.0	Erosion
112	Silicone sealant	RTV silicone	30	24	28.2	Erosion
117	Silicone rubber	RTV silicone	30	24	15.4	Erosion
118	Silicone rubber	RTV silicone	30	24	10.9	Erosion
75-76	Unfilled polyurethane (A)	Epoxy adhesive	30	24	46.1	Erosion
77-78	Unfilled polyurethane (A)	Epoxy adhesive	30	24	129.4	Erosion
40	Coal-tar polyurethane	Epoxy adhesive	30	24	76.0	Adhesion
41	Coal-tar polyurethane	Epoxy adhesive	30	24	76.0	Adhesion
119	Modified polyurethane	Epoxy adhesive	15	24	75.8	Adhesion
120	Modified polyurethane	Epoxy adhesive	15	24	77.4	Adhesion
81	Black polyurethane (A)	Bostik 1007	22 ± 2	24	219.8	Erosion
82	Black polyurethane (A)	Bostik 1007	22 ± 2	24	217.0	Erosion
125	Black polyurethane (A)	Bostik 1007	22 ± 2	12	310.0	Adhesion
83	Yellow polyurethane	Bostik 1007	22 ± 2	24	194.0	Erosion
84	Yellow polyurethane	Bostik 1007	22 ± 2	24	272.0	Erosion
126	Yellow polyurethane	Bostik 1007	22 ± 2	12	310.0	Adhesion
91	Polyimide film (A)	Epoxy adhesive	5	24	11.0	Erosion
92	Polyimide film (A)	Epoxy adhesive	5	24	6.3	Erosion
93	Polyimide film (A)	Epoxy adhesive	5	12	21.0	Erosion
94	Polyimide film (A)	Epoxy adhesive	5	12	10.7	Erosion
95	Phenoxy polymer (A)	-	2.8	24	98.9	Erosion
96	Phenoxy polymer (A)	-	2.8	24	50.3	Erosion
97	Phenoxy polymer (A)	-	2.8	12	58.6	Erosion
98	Phenoxy polymer (A)	-	2.8	12	65.2	Erosion
99	Phenoxy polymer (A)	-	9.0	24	43.2	Erosion
100	Phenoxy polymer (A)	-	9.0	24	42.9	Erosion
101	Phenoxy polymer (A)	-	9.0	12	85.2	Erosion
102	Phenoxy polymer (A)	-	9.0	12	85.2	Erosion
103-104	Phenoxy polymer (B)	-	6.0	24	None	No adhesion[3]
105-106	Phenoxy polymer (B)	-	6.0	12	None	No adhesion
107-108	Phenoxy polymer (C)	-	6.0	24	None	No adhesion
109-110	Phenoxy polymer (C)	-	6.0	12	None	No adhesion
79	Carborane-silicone	-	40.0	24	0	Complete failure
80	Carborane-silicone	-	40.0	24	1.4	Complete failure
C-1 & C-2	Specification neoprene (A)	Bostik 1007	20.0	2	157.8	Erosion
C-3 & C-4	Specification neoprene (A)	Bostik 1007	20.0	2	145.0	Erosion
127-128	Modified polyurethane	Primer 90-15-T	15	2	420.2	Erosion
129	Modified polyurethane	Primer 91-15-T	15	2	555.8	Erosion
130	Modified polyurethane	Primer 91-15-T	15	2	555.8	Erosion
131	Modified polyurethane	Primer 91-15-W	15	2	570.0	Erosion
132-133	Black polyurethane (B)	-	10	2	76.0	Adhesion
134	Black polyurethane (B)	-	10	2	141.6	Erosion
135	Black polyurethane (B)	-	10	2	58.4	Adhesion
136	Black polyurethane (B)	-	10	2	160.2	Erosion
137	Black polyurethane (B)	-	10	2	281.2	Erosion
138	Black polyurethane (B)	-	10	2	204.2	Erosion
139-140	Black polyurethane (C)	-	10	2	160.8	Erosion
155-156	Ionomer A	-	8	2	227.2	Erosion
157-158	Ionomer A	-	8	2	153.4	Erosion
159-160	Ionomer B	-	10	2	32.6	Erosion
161-162	Ionomer B	-	10	2	122.9	Erosion
163-164	Unfilled polyurethane (B)	Epoxy adhesive	30	2	90.0	Erosion

TABLE V (CONTD)

Specimen[1] No.	Material	Primer or Adhesive	Coating Thickness (mils)	Rainfall (inches/hour)	Time to[2] Failure (sec)	Type of Failure
165	Unfilled polyurethane (B)	Epoxy adhesive	30	2	279.8	Adhesion
166	Unfilled polyurethane (B)	Epoxy adhesive	30	2	490.3	Adhesion
167	Unfilled polyurethane (C)	Epoxy adhesive	30	2	422.0	Adhesion
168	Unfilled polyurethane (C)	Epoxy adhesive	30	2	1530.7	Erosion
197	Unfilled polyurethane (C)	Epoxy adhesive	30	2	1320.2	Erosion
180-181	Polyparaxylylene	-	5	2	3.0	Adhesion
182	Polyparaxylylene	-	5	2	4.8	Adhesion
183	Polyparaxylylene	-	3	2	4.8	Adhesion
184-185	Polyparaxylylene	-	3	2	1.6	Adhesion
186-187	Polyparaxylylene	-	1.6	2	0	Adhesion
188	Polyparaxylylene	-	1.6	2	-	Not run
189-190	Polyimide film (B)	-	1.0	2	244.2	Erosion
191-192	Polyimide film (B)	-	1.0	2	300.0	Erosion
204-205	Glass resin (A)	-	0.5	2	46.6	Erosion
206-207	Glass resin (B)	-	0.5	2	75.3	Erosion
208-209	Glass resin (A)w/TiO_2	-	0.75	2	46.6	Erosion
210-211	Glass resin (A)w/TiO_2	-	0.75	2	40.1	Erosion
351-352	Transparent urethane	Acrylic adhesive	10	2	360.0	Adhesion
353-354	Transparent urethane	Acrylic adhesive	15	2	780.0	Erosion
415	Specification neoprene (A)	Bostik	8.25	2	512.0	Slight erosion
416	White neoprene (B)	Bostik	5.8	2	267.0	Erosion
417	Spec. white neoprene (A)	Bostik	9.25	2	698.2	Erosion
418	White polyester	Bostik	10.0	2	698.2	Erosion

1. When two numbers are listed for a particular material, they represent two identical specimens which were evaluated together.

2. A failure of the coating is that moment when it is penetrated to the substrate.

3. Centrifugal force loosened coating before water was turned on.

TABLE VI

EXPOSURE TIMES FOR UNCOATED AND ELASTOMERIC-COATED 3/32" L. E. GLASS LAMINATE SPECIMENS

Specimen No.	Laminate Resin	Coating	Coating Thickness (mils)	Rainfall (inches/hour)	Time to failure (sec)	Comments
15	Polyester	-	-	24	26.90	Severe erosion thru upper plies
16	Polyester	-	-	24	44.35	Severe erosion thru upper plies
20	Polyester	-	-	24	3.0	Moderate erosion
21	Polyester	-	-	24	3.0	Moderate erosion
13	Polybenzimidazole (PBI)	-	-	24	3.7	Severe delamination (Specimen was low-resin content)
18	Polybenzimidazole (PBI)	-	-	24	43.0	Severe erosion
19	Polybenzimidazole (PBI)	-	-	24	43.0	Severe erosion
123	Polyester	-	-	2	None	Destroyed in test
198	Polyester	-	-	2	43.8	Moderate erosion
199	Polyester	-	-	2	43.8	Moderate erosion
11	Polyester	Unfilled urethane (D)	5	24	4.2	Erosion & Adhesion failure
12	Polyester	Unfilled urethane (D)	5	24	4.2	Erosion & Adhesion failure
14	Polyester	Spec. neoprene (A)	8	24	26.9	Complete penetration of coating
17	PBI	Spec. neoprene (A)	8	24	40.65	Complete penetration of coating
34	PBI	Advanced PBI resin	1	24	31.0	Erosion in plies
35	PBI	Advanced PBI resin	1	24	31.0	Erosion in plies
36	PBI	Polyimide varnish	2	24	44.5	Erosion in plies
37	PBI	Polyimide varnish	2	24	44.5	Erosion in plies
121	Polyester	Mod polyurethane	15	2	386.0	Complete adhesion loss
124	PBI	Polyimide varnish	2	2	386.0	Erosion completely thru laminate

TABLE VII

EXPOSURE TIMES FOR ELASTOMERIC-POLYMERIC MATERIALS ON CONFORMAL ALUMINUM SPECIMENS

Specimen No.	Coating	Primer or Adhesive	Coating Thickness (mils)	Rainfall (inches/hour)	Time to Failure (sec)	Comments
C-5&6	Specification neoprene (A)	Bostik	9-12	2	318.0	Erosion failure
C-7&8	Specification neoprene (A)	Bostik	9-12	2	314.4	Erosion failure
C-9&10	Specification neoprene (A)	Bostik	9-12	2	387.8	Erosion failure
C-11&12	Specification neoprene (A)	Bostik	17-20	2	359.6	Erosion failure
C-13&14	Specification neoprene (A)	Bostik	17-20	2	439.4	Erosion failure
C-15&16	Specification neoprene (A)	Bostik	17-20	2	288.0	Erosion failure
320-321	Polycarbonate	-	10	2	32.0	Erosion & adhesion loss
322-323	Polycarbonate	-	10	2	27.8	Erosion & adhesion loss
324-325	Polycarbonate	-	20	2	66.8	Erosion failure
326-327	Polycarbonate	-	20	2	76.4	Erosion failure
327-329	Polycarbonate	-	30	2	44.4	Erosion failure
330-331	Polycarbonate	-	30	2	85.8	Erosion failure
361-362	Polyurethane white paint	Epoxy resin	5	2	27.4	Adhesion failure
363-364	Polyurethane white paint	Epoxy resin	5	2	32.6	Adhesion failure
365-366	Polyurethane white paint	Epoxy resin	10	2	72.4	Adhesion failure
367-368	Polyurethane white paint	Epoxy resin	10	2	72.4	Adhesion failure
419-420	Black urethane tape	Epoxy adhesive	25	2	496.8	Erosion failure
421-422	Black urethane tape	Epoxy adhesive	25	2	405.0	Erosion failure
423-424	Black urethane tape	Epoxy adhesive	25	2	516.2	Adhesion failure
425-426	Black urethane tape	Epoxy adhesive	25	2	398.4	Erosion failure
471	Black urethane (A)	Bostik	10	2	167.0	Erosion failure
472	Black urethane (A)	Bostik	10	2	2471.4	Erosion failure
473	Black urethane (A)	Bostik	10	2	2295.8	Erosion failure
474	Black neoprene (C)	Bostik	10	2	208.0	Erosion failure
475-476	Black neoprene (C)	Bostik	10	2	131.2	Erosion failure
477-478	Black neoprene (C)	Bostik	20	2	259.0	Erosion failure
479	Black neoprene (C)	Bostik	20	2	253.2	Erosion failure
480	Black neoprene (C)	Bostik	40	2	253.2	Erosion failure
481-482	Black neoprene (C)	Bostik	40	2	338.6	Erosion failure
483-484	White neoprene (C)	Bostik	10	2	226.8	Erosion failure
485	White neoprene (C)	Bostik	10	2	216.6	Erosion failure
516-517	Cork sheet	Epoxy adhesive	35	2	8.2	Erosion failure
518-519	Cork sheet	Epoxy adhesive	35	2	6.4	Erosion failure
528-529	Nitroso-TiO_2	-	4-5	2	3.2	Erosion failure
530-531	Nitroso-TiO_2	-	4-5	2	3.0	Erosion failure
532-533	Abrasive tape (A)	Acrylic adhesive	14	2	139.6	Erosion failure
534-535	Abrasive tape (B)	Acrylic adhesive	15	2	133.6	Erosion failure
536-537	Abrasive tape (C)	Acrylic adhesive	16	2	122.8	Erosion failure
538-539	Abrasive tape (D)	Acrylic adhesive	16	2	132.2	Erosion failure
540-541	Abrasive tape (E)	Acrylic adhesive	14	2	153.0	Erosion failure
546-547	Preetched Teflon	Epoxy adhesive	35	2	19.0	Structural & erosion failure
548-549	Preetched Teflon	Epoxy adhesive	35	2	20.2	Structural & erosion failure
550-551	Unfilled urethane (E)	Epoxy adhesive	35	2	354.0	Erosion failure
552-553	Unfilled urethane (E)	Epoxy adhesive	35	2	450.4	Erosion failure
556-557	Fluidized bed epoxy	-	15	2	133.8	Erosion failure
558-559	Fluidized bed epoxy	-	15	2	124.4	Erosion failure
560-561	Fluidized bed silicone-epoxy	-	10	2	100.0	Erosion failure
562-563	Fluidized bed silicone-epoxy	-	10	2	100.0	Erosion failure
564-565	Plexiglass	Epoxy adhesive	62.5	2	119.2	Structural failure
588-589	Nitroso-stainless steel powder	-	3-4	2	11.2	Erosion failure
590-591	Nitroso-stainless steel powder	-	3-4	2	10.0	Erosion failure
622-623	Cork coated w/neoprene	Epoxy adhesive	46.5	2	8.0	Erosion failure
624-625	Cork coated w/neoprene	Epoxy adhesive	46.5	2	7.4	Erosion failure

TABLE VIII

EXPOSURE TIMES FOR ELASTOMERIC-POLYMERIC MATERIALS ON CONFORMAL LAMINATE SPECIMENS

Specimen No.	Coating	Primer or Adhesive	Laminate Resin	Coating Thickness (mils)	Rainfall (inches/hour)	Time to Failure (sec)	Comments
369-370	Molded neoprene (A)	Urethane adhesive	Epoxy	11	2	163.6	Adhesion failure
371-372	Molded neoprene (A)	Urethane adhesive	Epoxy	11	2	101.2	Erosion failure
373-374	Molded neoprene (A)	Epoxy adhesive	Epoxy	11	2	200.2	Erosion failure
375-376	Neoprene boot 10 mils neoprene 5 mils gum rubber 5 mils dacron cloth	Epoxy adhesive	Epoxy	20	2	17.4	Erosion failure
377	Neoprene boot 8 mils neoprene 10 mils gum rubber	Urethane adhesive	Epoxy	18	2	22.0	Erosion failure
378	Neoprene boot 8 mils neoprene 10 mils gum rubber	Epoxy adhesive	Epoxy	18	2	22.0	Moderate erosion
379	Neoprene boot 6 mils neoprene 10 mils gum rubber 4 mils urethane	Urethane adhesive	Epoxy	21	2	24.4	Adhesion failure
380	Neoprene boot 6 mils neoprene 10 mils gum rubber 4 mils urethane	Epoxy adhesive	Epoxy	21	2	86.0	Erosion failure
381-382	Molded neoprene (A)	Urethane adhesive	Epoxy	18	2	114.0	Erosion failure
383-384	Molded neoprene (A)	Urethane adhesive	Epoxy	18	2	121.8	Erosion failure
385	Neoprene boot 5 mils neoprene 5 mils Dacron cloth	Urethane adhesive	Epoxy	10	2	128.4	Erosion failure
386	Neoprene boot 5 mils neoprene 5 mils Dacron cloth	Urethane adhesive	Epoxy	10	2	163.0	Erosion failure
387-388	Neoprene boot w/neoprene backing 10 mils neoprene 5 mils gum 5 mils Dacron cloth	Epoxy adhesive	Epoxy	20	2	78.0	Erosion failure
389	Special compound neoprene boot	Epoxy adhesive	Epoxy	12	2	363.0	Erosion failure
390	Special compound neoprene boot	Epoxy adhesive	Epoxy	18	2	363.0	Moderate erosion
391-392	Sprayed neoprene (B)	-	Epoxy	13	2	180.8	Erosion and adhesion failure
393-394	Sprayed neoprene (B)	-	Epoxy	13	2	243.6	Erosion and adhesion failure
395-396	White urethane paint (A)	-	Epoxy	5	2	57.8	Erosion failure
397-398	White urethane paint (B)	-	Epoxy	5	2	35.2	Erosion failure
399-400	White urethane paint (B)	-	Epoxy	12	2	36.8	Erosion failure
401	Neoprene boot	Urethane adh.	Epoxy	20	2	17.0	Adhesion failure
402	Neoprene boot	Urethane adh.	Epoxy	20	2	17.0	Erosion failure
403-404	Sprayed urethane	-	Epoxy	5	2	76.8	Erosion failure
405-406	Neoprene boot, Dacron backing	Epoxy adhesive	Epoxy	10	2	64.0	Erosion failure
407	Urethane boot	Urethane adh.	Epoxy	10	2	17.6	Adhesion failure
408	Urethane boot	Epoxy adhesive	Epoxy	10	2	44.0	Erosion failure
486-487	Black urethane (A)	Bostik	Polyester	10	2	160.6	Erosion failure
488	Black urethane (A)	Bostik	Polyester	10	2	174.4	Erosion failure
489	Black neoprene (C)	Bostik	Polyester	10	2	87.4	Erosion failure
490-491	Black neoprene (C)	Bostik	Polyester	10	2	135.4	Erosion failure
492-493	Black neoprene (C)	Bostik	Polyester	20	2	145.4	Moderate erosion
494	Black neoprene (C)	Bostik	Polyester	20	2	186.4	Erosion failure
495	Black neoprene (C)	Bostik	Polyester	40	2	186.4	Erosion failure in upper layer
496-497	Black neoprene (C)	Bostik	Polyester	40	2	245.0	Erosion failure in upper layer
498-499	White neoprene (C)	Bostik	Polyester	10	2	264.4	Erosion failure
500	White neoprene (C)	Bostik	Polyester	10	2	414.4	Erosion failure
513	Epoxy-E glass laminate coated with epoxy-stainless steel fabric arranged in longitudinal direction			-	2	79.4	Erosion through fabric & plies

TABLE VIII (CONTD)

Specimen No.	Coating	Primer or Adhesive	Laminate Resin	Coating Thickness (mils)	Rainfall (inches/hour)	Time to Failure (sec)	Comments
514	Epoxy-E glass laminate coated with epoxy-stainless steel fabric arranged in circular direction			-	2	79.4	Erosion through fabric & plies
515	Epoxy-E glass laminate coated with epoxy-stainless steel fabric arranged in circular direction			-	2	51.4	Erosion through fabric & plies
409-410	Uncoated epoxy laminate (A)			-	2	43.4	Penetration of 4 plies of fabric
444-445	Uncoated Aluminum phosphate laminate			-	2	22.0	Eroded completely through
447-448	Polyimide-E glass laminate			-	2	49.0	Eroded completely through
463-464	Polyimide-E glass laminate			-	2	42.0	Eroded completely through
449-450	Epoxy-E glass laminate (B)			-	2	60.0	Penetration of 5 plies of fabric
503-504	Uncoated polyester laminate			-	2	91.0	Eroded completely through
649-650	Plexiglass molded specimen			125	2	112.4	Erosion through specimen
651-652	Polyvinylchloride molded specimen			125	2	96.0	Erosion through specimen
653-654	Kel-F molded specimen			125	2	370.0	Erosion through specimen

TABLE IX

EXPOSURE TIMES FOR CERAMIC MATERIALS ON ALUMINUM SUBSTRATES

Specimen No.	Material	Primer or Adhesive	Coating Thickness (mils)	Rainfall Rate (inches/hour)	Time to Failure (sec)	Comments
		1/8-in. L. E. Specimens				
46	Plasma-sprayed Al_2O_3	-	18	24	55.0	Coating completely gone
145	Rokide A sprayed alumina	-	10	2	11.8	Erosion failure
146	Rokide A sprayed alumina	-	10	2	11.8	Erosion failure
147	Rokide A alumina impregnated w/Epon 1031	-	10	2	10.0	Erosion failure
148	Rokide A alumina impregnated w/Epon 1031	-	10	2	10.0	Erosion failure
193	Vacuum evaporated alumina	-	7-8000 A°	2	24.8	Coating gone
194	Vacuum evaporated alumina	-	8-10,000 A°	2	24.8	Coating gone
212	Plasma-sprayed Al_2O_3 (High velocity argon electrode-550 amps)	-	30	2	600.0	Adhesion failure
213	Plasma-sprayed Al_2O_3 (High velocity argon electrode-550 amps)	-	30	2	600.0	Adhesion failure
214	Plasma-sprayed Al_2O_3 (High velocity argon electrode-400 amps)	-	15	2	137.0	Erosion failure
215	Plasma-sprayed Al_2O_3 (Standard nitrogen electrode)	-	20	2	137.0	Erosion failure
265	Plasma sprayed Al_2O_3	-	11	2	97.0	Erosion failure
266	Plasma sprayed Al_2O_3		15-20	2	97.0	Erosion failure
267	Plasma sprayed Al_2O_3	-	9	2	95.4	Erosion failure
268	Plasma sprayed Al_2O_3	-	7	2	95.4	Erosion failure
269	Plasma sprayed ZrO_2	-	7	2	93.0	Erosion failure
270	Plasma sprayed ZrO_2	-	3	2	240.0	Erosion failure
271	Plasma sprayed ZrO_2		7	2	240.0	Erosion failure
272	Plasma sprayed ZrO_2	-	12	2	93.0	Erosion failure
276	Plasma sprayed Al_2O_3	Porcelain enamel	30	2	1058.0	Erosion to substrate
277	Plasma sprayed Al_2O_3	Porcelain enamel	30	2	1058.0	Erosion to substrate
280	Rokide A alumina	-	30	2	202.4	Erosion failure
281	Rokide A alumina	-	30	2	36.2	Adhesion failure
284	Rokide A alumina w/organic resin	-	30	2	600.0	Resin gone, ceramic eroded
285	Rokide A alumina w/organic resin	-	30	2	600.0	Erosion failure
288	Rokide A alumina	Secondarily bonded	30	2	1433.0	Erosion on surface
289	Rokide A alumina	Secondarily bonded	30	2	1433.0	Erosion failure
290	Rokide A alumina w/organic resin	Secondarily bonded	30	2	1354.0	Erosion failure
291	Rokide A alumina w/organic resin	Secondarily bonded	30	2	1354.0	Erosion failure
293	Rokide A alumina sintered 4 hrs @ 2500°F	Secondarily bonded	30	2	52.0	Adhesion failure
294	Rokide A alumina sintered 4 hrs @ 2500°F	Secondarily bonded	30	2	203.2	Slight erosion
295	Rokide A alumina w/organic resin sintered 4 hrs @ 2500°F	Secondarily bonded	30	2	202.2	Erosion failure
296	Rokide A alumina w/organic resin sintered 4 hrs @ 2500°F	Secondarily bonded	30	2	52.0	Resin gone, coating cracked
297	Plasma sprayed Al_2O_3	Pickled Al	25	2	227.4	Adhesion failure
298	Plasma sprayed Al_2O_3	Grit blasted Al	32	2	731.4	Erosion failure
299	Plasma sprayed Al_2O_3	Grit blasted Al	40	2	731.4	Erosion failure
300	Plasma sprayed Al_2O_3	Green enamel primer	24	2	222.6	Adhesion failure
301	Plasma sprayed Al_2O_3	Green enamel primer	22	2	326.2	Adhesion failure
302	Plasma sprayed Al_2O_3	Grey enamel w/grit blast	34	2	1140.8	Erosion failure
303	Plasma sprayed Al_2O_3	Grey enamel w/grit blast	37	2	890.0	Erosion failure
554	Chemically strengthened alumina	-	125	2	8400.0	Chipping away of ceramic
555	Chemically strengthened alumina w/Cr_2O_3	-	125	2	8400.0	Slight wear on surface

TABLE IX (CONTD)

Specimen No.	Material	Primer or Adhesive	Coating Thickness (mils)	Rainfall Rate (inches/hour)	Time to Failure (sec)	Comments
		1/32-in. L. E. Specimens				
141	Rokide A sprayed alumina	-	10	2	269.2	Erosion failure
142	Rokide A sprayed alumina	-	10	2	269.2	Erosion failure
143	Rokide A alumina impregnated w/Epon 1031	-	10	2	56.0	Erosion failure
144	Rokide A alumina impregnated w/Epon 1031	-	10	2	56.0	Erosion failure
278	Rokide A alumina	-	30	2	121.8	Erosion failure
279	Rokide A alumina	-	30	2	121.8	Erosion failure
282	Rokide A alumina w/organic resin	-	30	2	463.2	Resin gone, ceramic eroded
283	Rokide A alumina w/organic resin	-	30	2	463.2	Erosion failure
286	Rokide A alumina	Secondarily bonded	30	2	575.6	Severe erosion on edge
287	Rokide A alumina w/organic resin	Secondarily bonded	30	2	2100.0	Severe erosion on edge
292	Rokide A alumina w/organic resin sintered 4 hrs @ 2500°F	Secondarily bonded	30	2	575.6	Erosion failure
		Conformal Specimens				
336	Rokide A alumina	-	30	2	101.4	Erosion evident, some adhesion loss
337	Rokide A alumina	-	30	2	101.4	Adhesion failure

Notes: Specimens 282, 283, 284, 285, 287, 290, 291, 292, 295 and 296 were impregnated with a high temperature organic resin after spraying to reduce porosity.

Approximately 110 specimens of various plasma-sprayed materials on the conformal aluminum and laminate specimens have been evaluated by this Laboratory in support of Contract AF33(615)-3342 for research for improved, dense, ceramic rain erosion resistant coatings being conducted by the Brunswick Corp. Data on these specimens will be documented in reports from this contract.

TABLE X

EXPOSURE TIMES FOR CERAMIC MATERIALS ON LAMINATE SUBSTRATES

Specimen No.	Material	Substrate	Coating Thickness (mils)	Rainfall Rate (inches/hour)	Time to Failure (sec)	Comments
30	Flame sprayed Al_2O_3	PBI laminate	30	24	286.0	Erosion failure
31	Flame sprayed Al_2O_3	PBI laminate	30	24	286.0	Erosion failure
38	94% Al_2O_3 - 6% Epoxy	PBI laminate	15	24	13.0	Erosion failure
39	94% Al_2O_3 - 6% Epoxy	Polyester laminate	15	24	13.0	Erosion failure
47	Plasma sprayed Al_2O_3	AlPO laminate	10	24	2.0	Erosion failure
48	Plasma sprayed Al_2O_3	AlPO laminate	15	24	2.0	Erosion failure
49	Plasma sprayed Al_2O_3	PBI laminate	15	24	13.5	Erosion failure
50	Plasma sprayed Al_2O_3	PBI laminate	15	24	13.5	Erosion failure
85	Flame sprayed Al_2O_3	PBI laminate	30	24	73.0	Erosion failure
86	Flame sprayed Al_2O_3	PBI laminate	30	12	156.6	Erosion failure
87	Flame sprayed Al_2O_3	PBI laminate	30	24	-	Destroyed during test
88	Flame sprayed Al_2O_3	PBI laminate	30	24	73.0	Erosion failure
89	Flame sprayed Al_2O_3	PBI laminate	30	12	156.0	Erosion failure
149	Rokide A alumina	Polyester laminate	10	2	840.9	Erosion failure
150	Rokide A alumina	Polyester laminate	10	2	240.9	Erosion failure
151	Rokide A alumina w/Epon 1031	Polyester laminate	10	2	497.2	Erosion failure
152	Rokide A alumina w/Epon 1031	Polyester laminate	10	2	1097.2	Erosion failure
216	Flame sprayed Al_2O_3	PBI laminate	30	2	147.0	Erosion failure
217	Flame sprayed Al_2O_3	PBI laminate	30	2	147.0	Erosion failure
218	Flame sprayed Al_2O_3	PBI laminate	30	4	28.2	Adhesion failure
219	Flame sprayed Al_2O_3	PBI laminate	30	4	28.2	Slight polishing
221	Flame sprayed Al_2O_3	PBI laminate	30	6	136.0	Penetration into laminate
222	Flame sprayed Al_2O_3	PBI laminate	30	6	136.0	Penetration into laminate
332	Rokide A alumina	PBI laminate	30	2	35.2	Erosion failure
333	Rokide A alumina	PBI laminate	30	2	35.2	Erosion failure
334	Rokide A alumina	Polyester laminate	30	2	11.0	Erosion failure
335	Rokide A alumina	Polyester laminate	30	2	11.0	Moderate erosion

All specimens are 3/32-in. leading edge configuration.

TABLE XI

EXPOSURE TIMES OF METAL SPECIMENS

Specimen No.	Material	Specimen Configuration	Coating Thickness (mils)	Rainfall Rate (inches/ hour)	Time of Exposure (sec)	Comments
26	2024 aluminum	1/8" L. E. radius	-	24	900.0	Moderate pitting
27	2024 aluminum	1/8" L. E. radius	-	24	900.0	Moderate pitting
28	2024 aluminum	1/8" L. E. radius	-	12	1800.0	Severe pitting
29	2024 aluminum	1/8" L. E. radius	-	12	1800.0	Severe pitting
42	403 stainless steel	0.015" L. E. radius	-	24	1800.0	No visible effect
43	403 stainless steel	0.025" L. E. radius	-	24	1800.0	No visible effect
44	titanium-6Al-4V	0.015" L. E. radius	-	24	1800.0	No visible effect
45	titanium-6Al-4V	0.025" L. E. radius	-	24	1800.0	No visible effect
122	2024 aluminum	1/8" L. E. radius	-	2	578.5	Very small pits
171-172	Electroplated nickel	1/8" L. E. radius	8	2	3600.0	No effect; wash effect
173-174	Electroplated nickel	1/8" L. E. radius	16	2	3600.0	No effect; wash effect
175	Electroplated nickel	3/32" L. E. polyester laminate	6	2	3948.2	No effect
176	Electroplated nickel	3/32" L. E. polyester laminate	6	2	1800.0	Small hole in coating
178	Electroplated chromium	3/32" L. E. polyester laminate	6	2	1421.0	Penetration to laminate
179	Electroplated chromium	3/32" L. E. polyester laminate	6	2	30.0	Adhesion failure
256	Electroplated nickel	3/32" L. E. polyester laminate	10	2	370.6	Adhesion loss
257	Electroplated nickel	3/32" L. E. polyester laminate	10	2	234.0	Adhesion loss
258	Electroplated nickel	3/32" L. E. polyester laminate	10	2	136.0	Adhesion loss
355	Electroplated nickel	3/32" L. E. PBI laminate	2.2	2	411.8	Erosion failure
356	Electroplated nickel	3/32" L. E. PBI laminate	2.2	2	411.8	Erosion failure
357	Electroplated nickel	3/32" L. E. PBI laminate	6.0	2	2760.0	Erosion failure
358	Electroplated nickel	3/32" L. E. PBI laminate	6.0	2	2760.0	Erosion failure
455	Electroplated nickel	3/32" L. E. PBI laminate	6.3	2	741.6	Adhesion failure
456	Electroplated nickel	3/32" L. E. PBI laminate	6.3	2	1480.0	Erosion failure
457	Electroplated nickel	3/32" L. E. PBI laminate	9.1	2	2760.0	Erosion failure
458	Electroplated nickel	3/32" L. E. PBI laminate	9.1	2	10,000	Erosion failure
520	Electroplated nickel	3/32" L. E. PBI laminate	6	2	5400	Erosion failure
521	Electroplated nickel	3/32" L. E. PBI laminate	6	2	22,980	No erosion
522	Electroplated nickel	3/32" L. E. PBI laminate	12	2	33,000	No erosion
523	Electroplated nickel	3/32" L. E. PBI laminate	12	2	19,020	Erosion failure
524	Electroplated nickel	3/32" L. E. PBI laminate	16	2	7200	No erosion
525	Electroplated nickel	3/32" L. E. PBI laminate	16	2	7200	No erosion
526	Electroplated nickel	3/32" L. E. polyester laminate	16	2	3600	No erosion
527	Electroplated nickel	3/32" L. E. polyester laminate	16	2	3600	No erosion
304	Plasma-sprayed nickel aluminide	1/8" L. E. aluminum	14-15	2	13.4	Adhesion failure
305	Plasma-sprayed nickel aluminide	1/8" L. E. aluminum	12-13	2	76.0	Penetration of coating
306-307	Plasma-sprayed nickel aluminide-tungsten carbide	1/8" L. E. aluminum	10-11	2	20.4	Adhesion failure
338-339	Beryllium	0.025" L. E. radius	-	6	1800.0	No effect

TABLE XI (CONTD)

Specimen No.	Material	Specimen Configuration	Coating Thickness (mils)	Rainfall Rate (inches/hour)	Time of Exposure (sec)	Comments
427-428	Plasma-sprayed nickel aluminum	Conformal aluminum	3	2	67.2	Erosion failure
453-454	Plasma-sprayed nickel aluminum-zirconia	Conformal aluminum	1	2	68.0	Erosion failure
655	Vapor deposited silicon carbide	Conformal graphite	1	2	265.6	Erosion failure

Note: Exposures on nickel-plated specimens which exhibit no effect after the times shown are being continued

CODE LIST--RAIN EROSION SPECIMENS

Specimen Nos.	Report Designation	Coating Material	Supplier
	Table V		
22-25, 415	Specification neoprene A	Goodyear 23-56	Goodyear Tire & Rubber Co.
C-1 thru C-16			
67-70	Spec. white neoprene A	Gaco N-83 white	Gates Engineering Co.
71-74	Specification neoprene B	Gaco N-700-9	Gates Engineering Co.
51-54	Fluorosilicone	Q-94-003	Dow Corning
55-56	Dimethylsilicone	Q-92-009	Dow Corning
115, 116			
59-62	Dimethylsilicone gum	Q-90-092	Dow Corning
113, 114			
63-66	Silicone	Q-90-090	Dow Corning
111-112	Silicone sealant	Q-90-031	Dow Corning
117, 118	Silicone rubber	S-950	Dow Corning
75-78	Unfilled polyurethane A	P. O. 655	Armstrong Cork
40, 41, 119	Coal tar & modified	-	Amicon Corporation
120, 127-131	Polyurethanes		
81, 82, 125	Black urethane A	Estane 4071	B. F. Goodrich
471-473			
83, 84, 126	Yellow urethane	Estane	B. F. Goodrich
91-94	Polyimide A	H-film	du Pont
95-102	Phenoxy A	Phenoxy-A	Union Carbide
103-106	Phenoxy B	Phenoxy-T-5	Union Carbide
107-110	Phenoxy C	Phenoxy-T-8	Union Carbide
79-80	Carborane-silicone	-	Thiokol
132-138	Black urethane B	KE-7802	Goodrich Aerospace
139-140	Black polyurethane C	KE-7801	Goodrich Aerospace
155-158	Ionomer A	Surlyn A ER-1601	du Pont
159-162	Ionomer B	Surlyn A	du Pont
163-166	Unfilled polyurethane B	LD-550	du Pont
167, 168, 197	Unfilled polyurethane C	ECD-498	du Pont
180-188	Polyparaxylylene	Parylene C	Union Carbide
189-192	Polyimide B	-	Solar
204, 205	Glass resin A	Resin 100	Owens-Illinois
209-211			
206-207	Glass resin B	Resin 650	Owens-Illinois
351-354	Transparent urethane	-	3M
416	White neoprene B	-	Goodyear Tire & Rubber Co.
418	White polyester	-	Grumman
	Table VI		
11, 12	Unfilled urethane D	Proseal 798	Coast Mfg.
34, 35	Advanced PBI resin	AFR-151	Narmco
36, 37, 124	Polyimide varnish	"ML" varnish	du Pont
121	Modified polyurethane	-	Amicon
	Table VII		
320-331	Polycarbonate	Lexan	Union Carbide
361-368	Polyurethane white paint	XA-5094	3M
419-426	Black urethane tape	-	3M
471-473	Black urethane A	Estane XA4071-1	B. F. Goodrich
474-482	Black neoprene C	Neoprene XA4071-2	B. F. Goodrich
483-485	White neoprene C	Neoprene XA4071-4	B. F. Goodrich
516-519	Cork sheet	AC-2755	Armstrong
532-533	Abrasive tape A	Urethane w/abrasive particles	3M
534-535	Abrasive tape B	Urethane w/abrasive particles	3M
536-537	Abrasive tape C	Urethane w/abrasive particles	3M
538-539	Abrasive tape D	Urethane w/abrasive particles	3M
540-541	Abrasive tape E	Urethane w/abrasive particles	3M
528-531	Nitroso-TiO_2	Nitroso copolymer	Thiokol
546-549	Teflon	-	du Pont
550-553	Unfilled urethane E	Adiprene L-315	du Pont
556-559	Fluidized bed epoxy	E627	Armstrong Products

CODE LIST--RAIN EROSION SPECIMENS (CONTD)

Specimen Nos.	Report Designation	Coating Material	Supplier
	Table VII		
560-563	Fluidized bed silicone-epoxy	-	Dow Corning
564-565	Plexiglass	-	AFML
588-591	Nitroso-stainless steel	Nitroso terpolymer	Thiokol
	Table VIII		
369-374	Molded neoprene A	Goodyear 23-56	Douglas
395-396	White urethane paint A	Catalac	Douglas
397-400	White urethane paint B	Prestec	Douglas
	Table IX		
46, 212-215	Plasma sprayed Al_2O_3	-	Brunswick
265-268	Plasma sprayed Al_2O_3	-	Quantum
269-272	Plasma sprayed Zr_2O_3	-	Quantum
145-148	Rokide A alumina	-	Naval Ordnance Lab.
280-296	Rokide A alumina	-	Goodyear Aerospace
276, 277 297-303	Plasma sprayed Al_2O_3	-	Brunswick
141-144	Rokide A alumina	-	NOL
279-292 336, 337	Rokide A alumina	-	Goodyear Aerospace
554-555	Chem strengthened Al_2O_3	-	Linden Labs.
	Table X		
30, 31, 85-89 216-222	Flame-sprayed Al_2O_3	-	Narmco
38-39	94% Al_2O_3-6% Epoxy	-	Amicon
47-50	Plasma sprayed Al_2O_3	-	Brunswick
149-152	Rokide A alumina	-	NOL
332-335	Rokide A alumina	-	Goodyear Aerospace
	Table XI		
304-305	Plasma sprayed nickel aluminide	-	Monsanto
306-307	Plasma sprayed nickel aluminide-tungsten carbide	-	Monsanto
427-428	Plasma sprayed nickel-aluminum	-	Monsanto
453-454	Plasma sprayed nickel-aluminum-zirconia	-	Monsanto
655	Vapor deposited silicon carbide	-	Texas Instrument

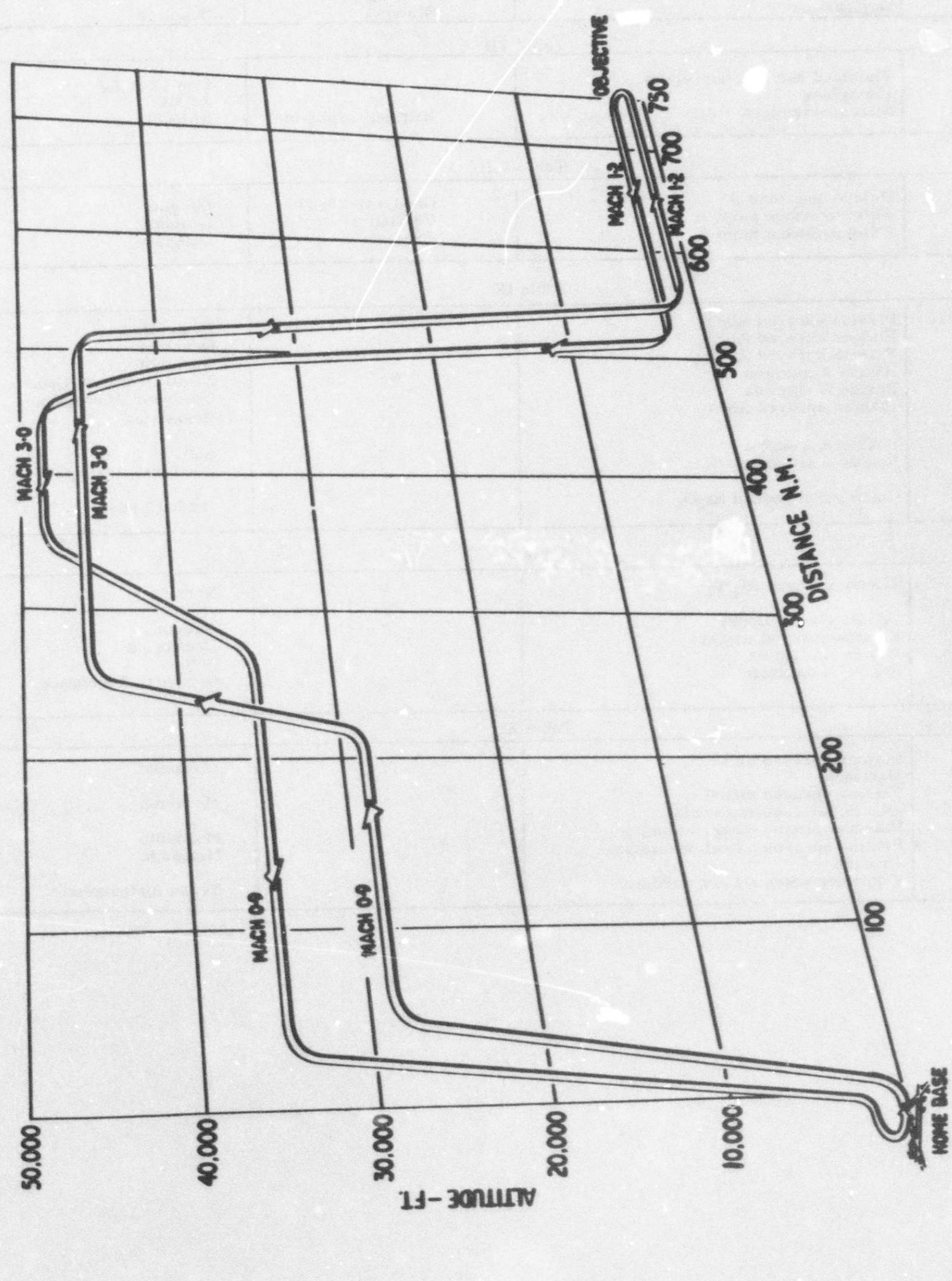


Figure 1. Hypothetical Flight Plan for a M3 Aircraft

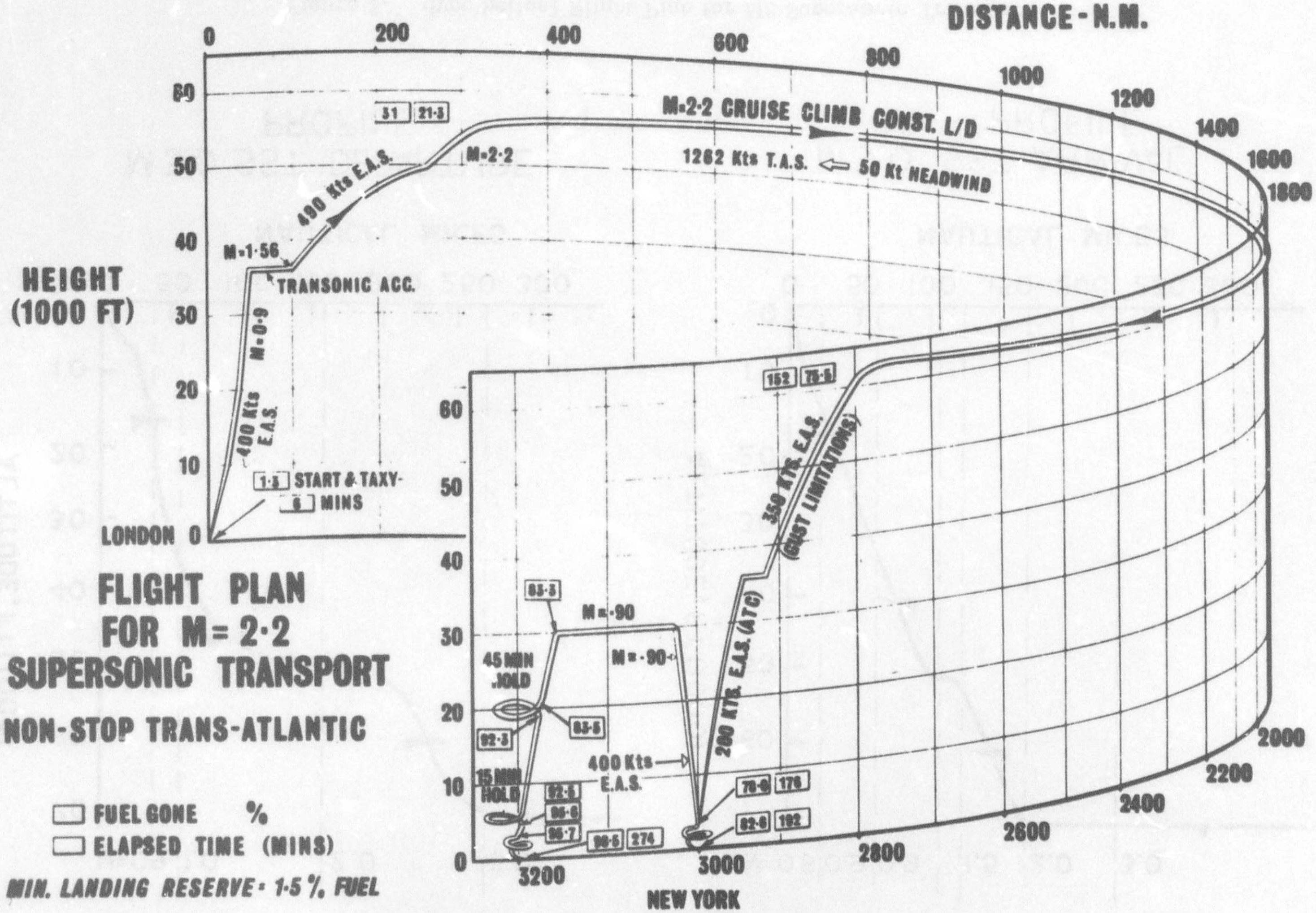


Figure 2. Flight Plan for M2. 2 Supersonic Transport

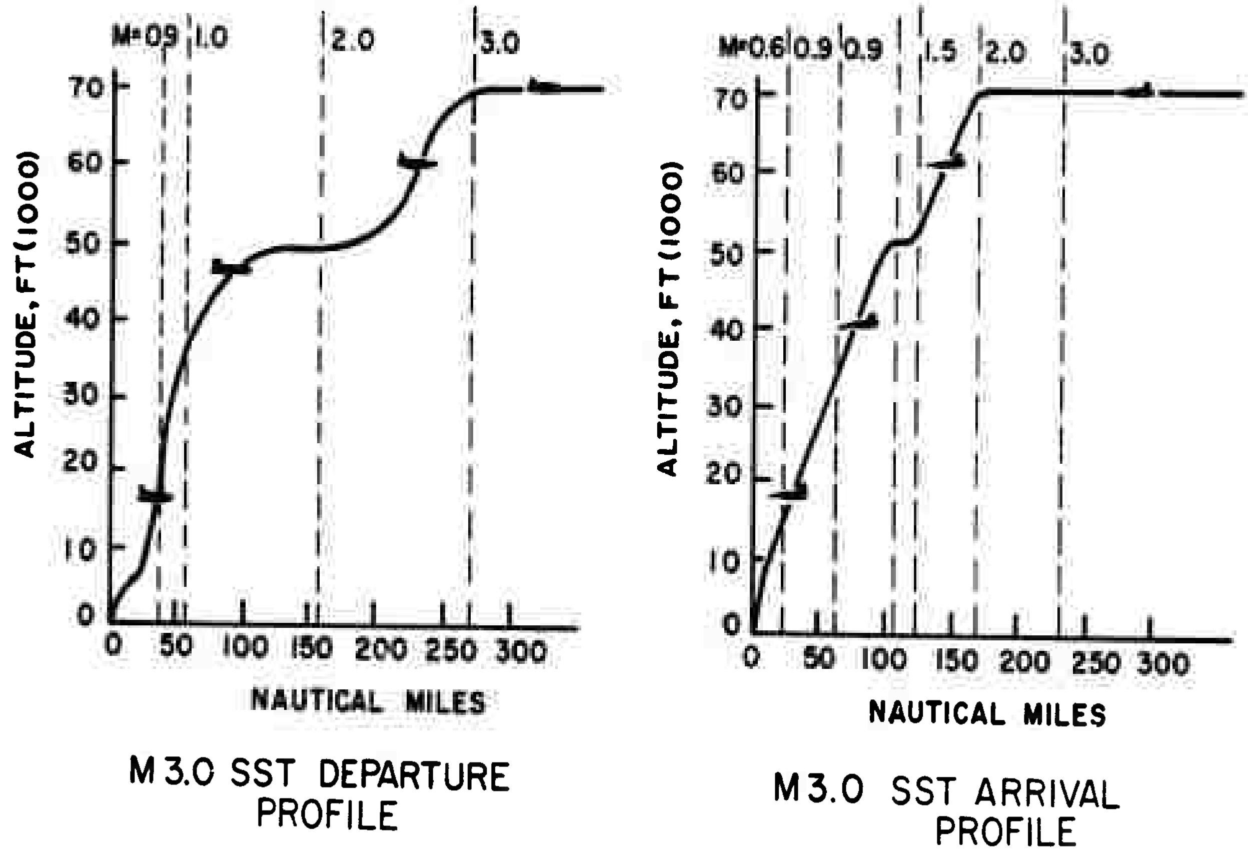


Figure 3. Hypothetical Flight Plan for M3 Supersonic Transport

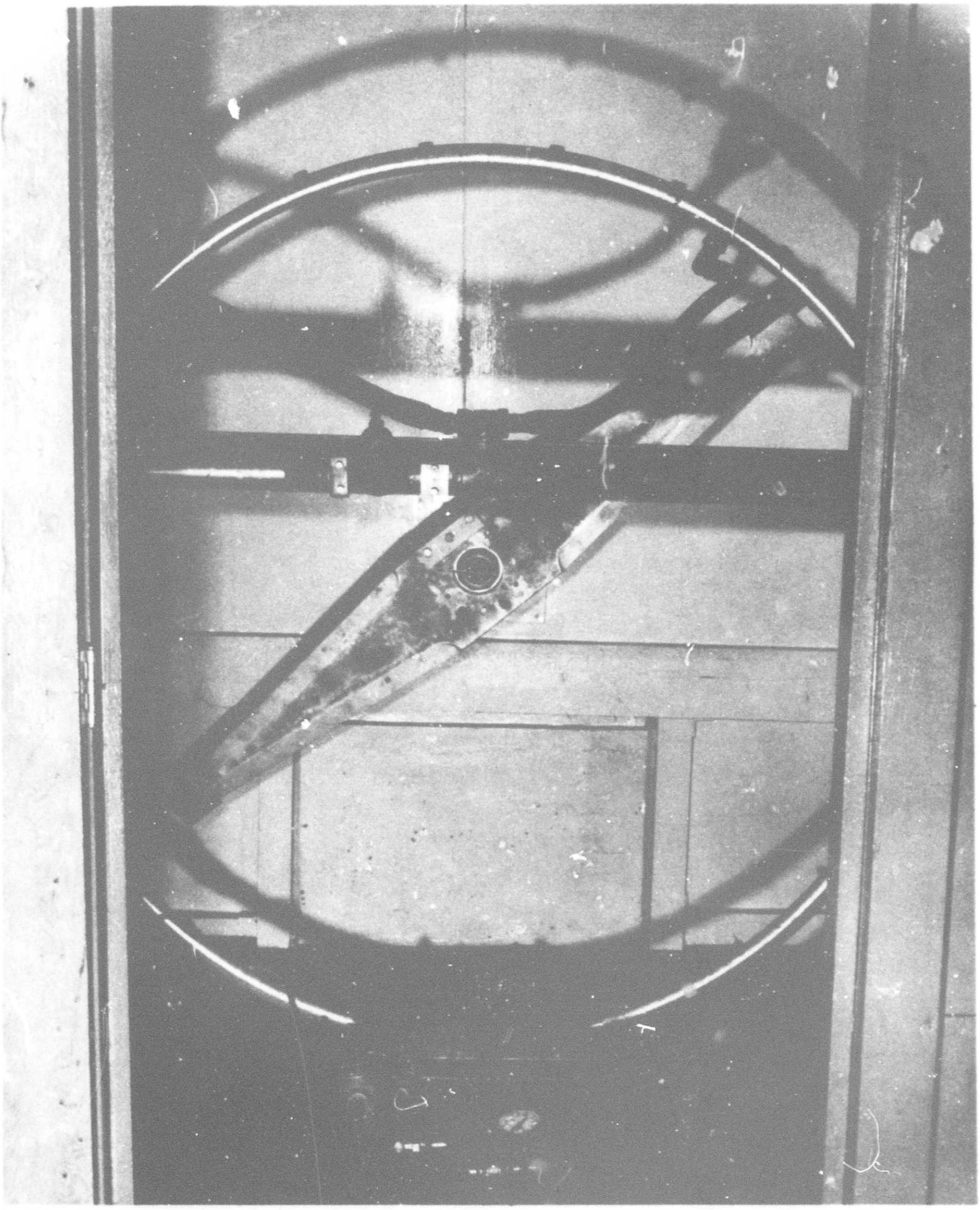


Figure 4. 6 Foot Diameter Rain Erosion Facility (Inside of Test Enclosure)

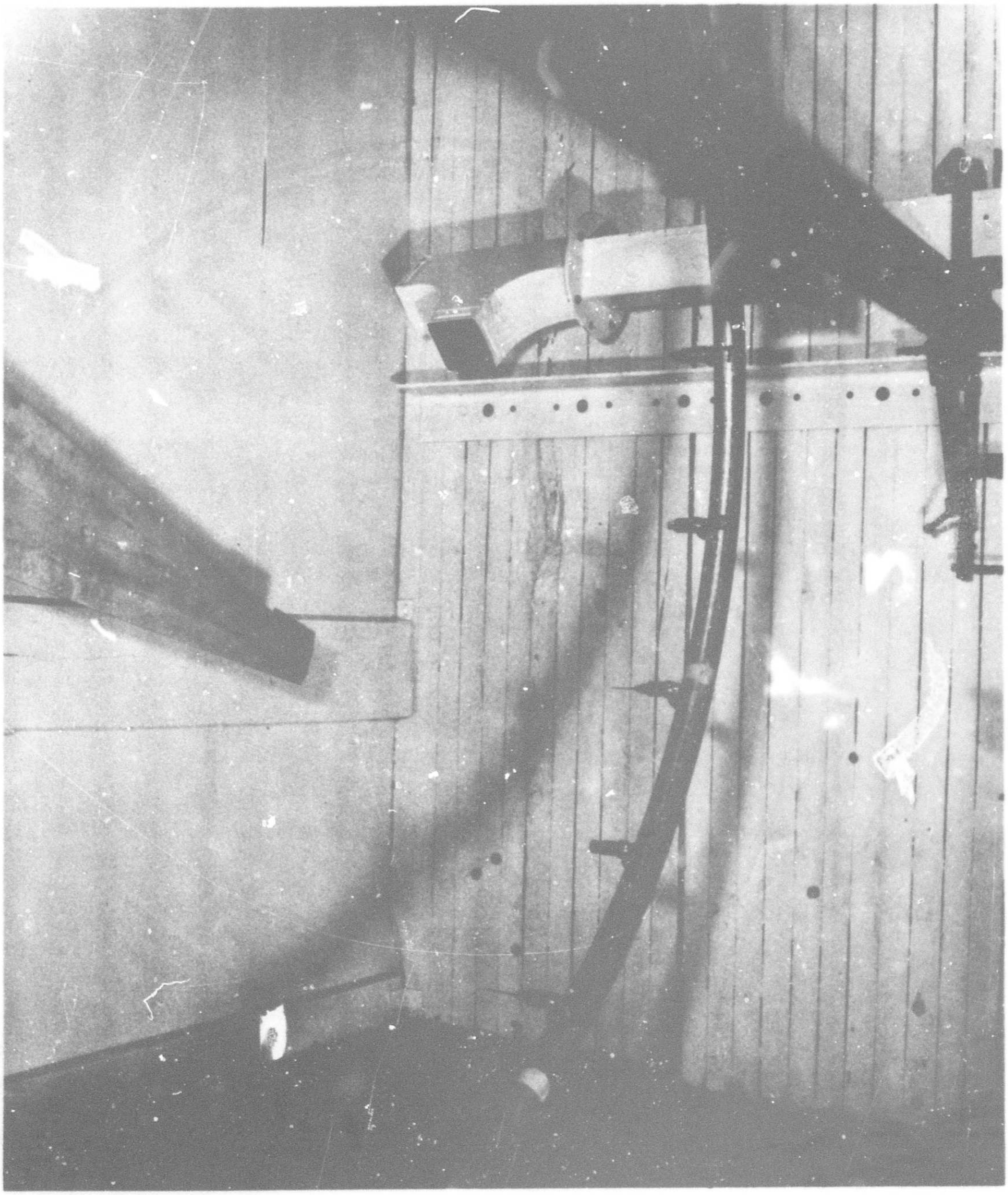


Figure 5. 6-Foot Diameter Rain Erosion Facility (Spray Ring, Whirling-Arm, and Periscope Tube)

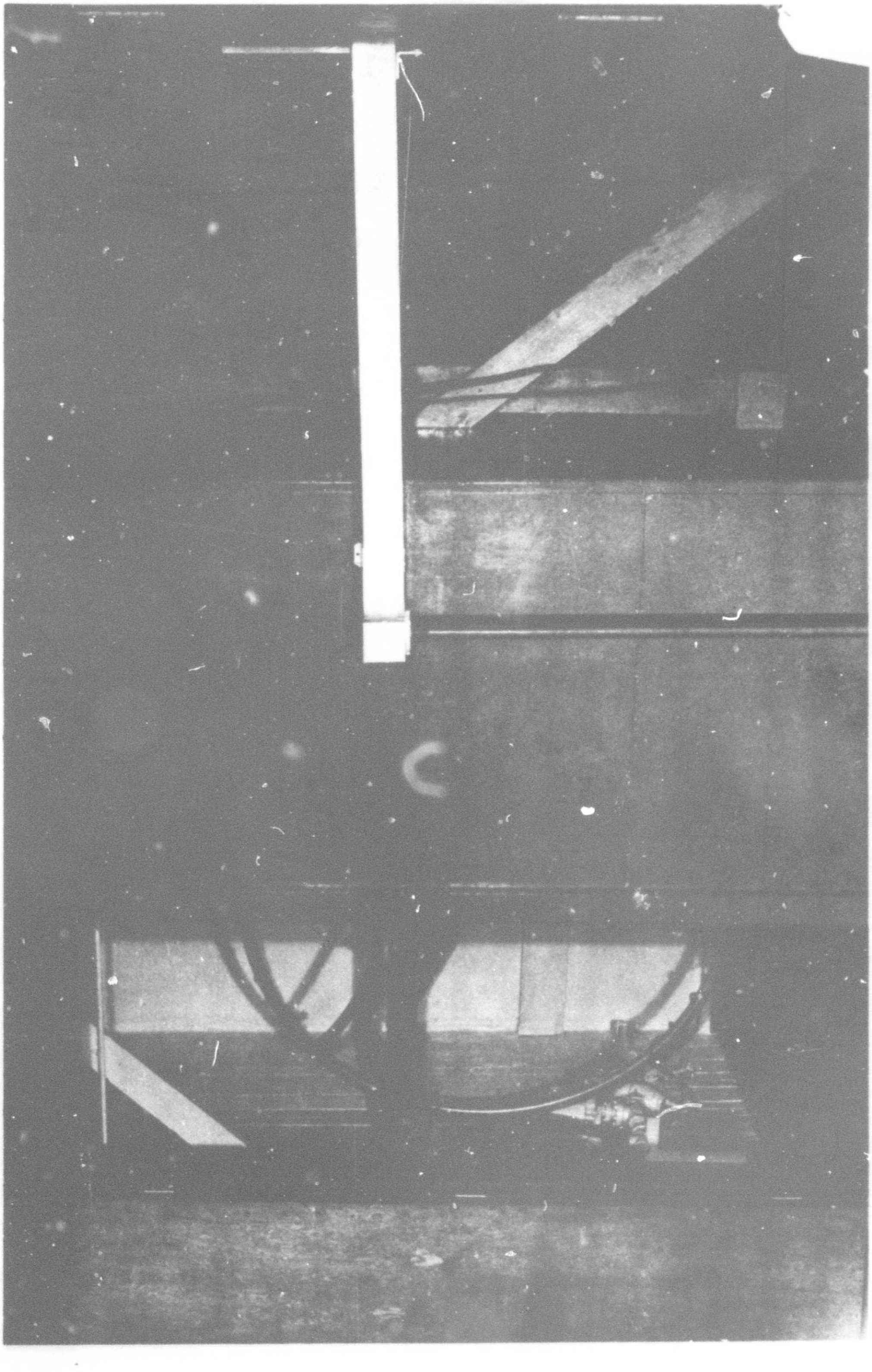


Figure 6. 6-Foot Diameter Rain Erosion Facility (Test Enclosure and Periscope Tube Location)

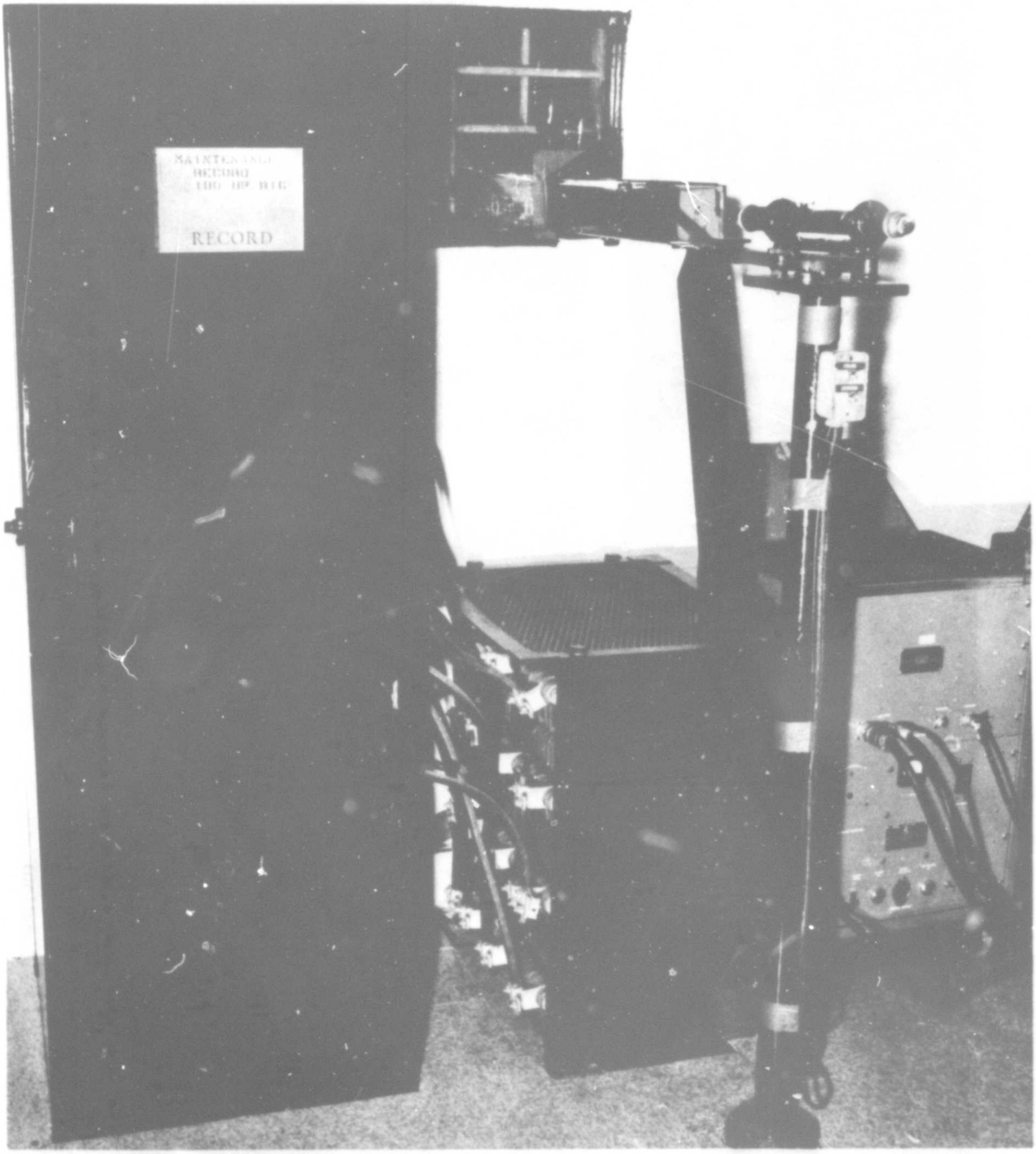


Figure 7. 6-Foot Diameter Rain Erosion Facility Control Room (Telescope Mount, Strobe Power Unit, and Motor Load Bank)

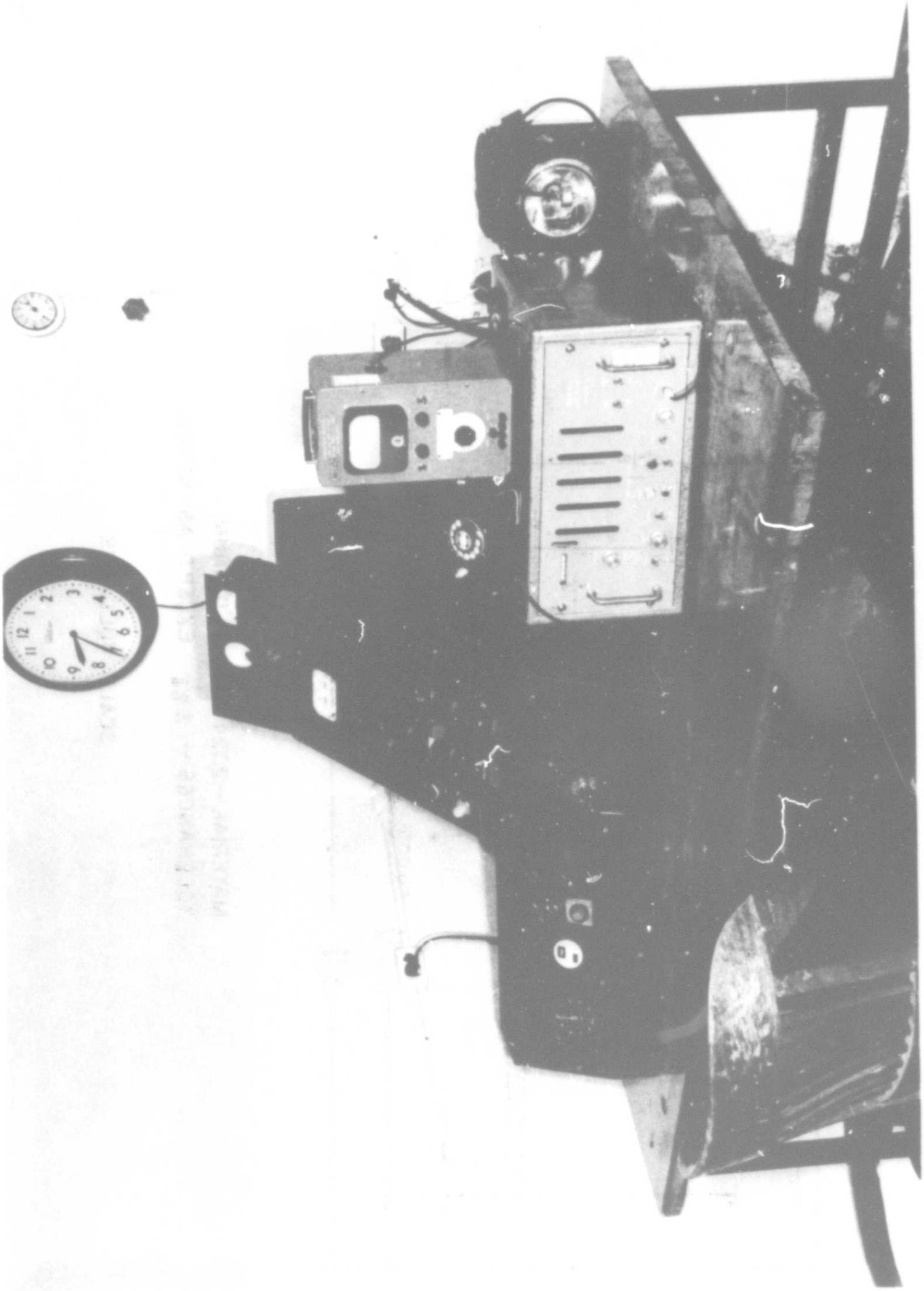
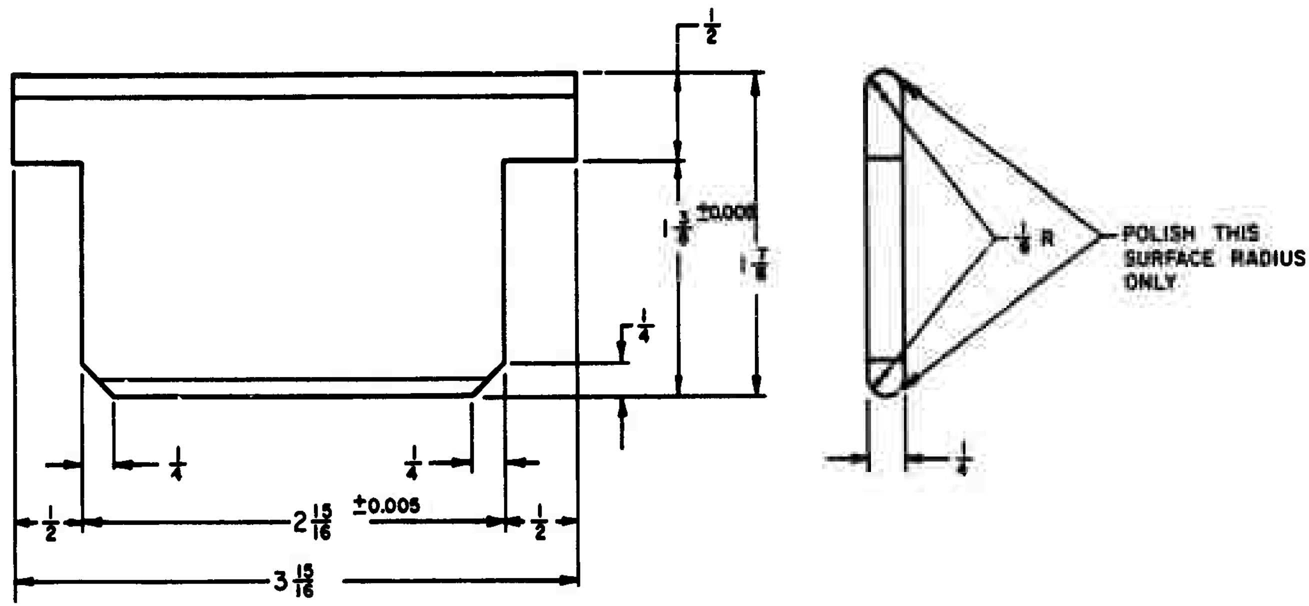


Figure 8. 6-Foot Diameter Rain Erosion Facility Control Room (Motor Controls and Test Instrumentation)

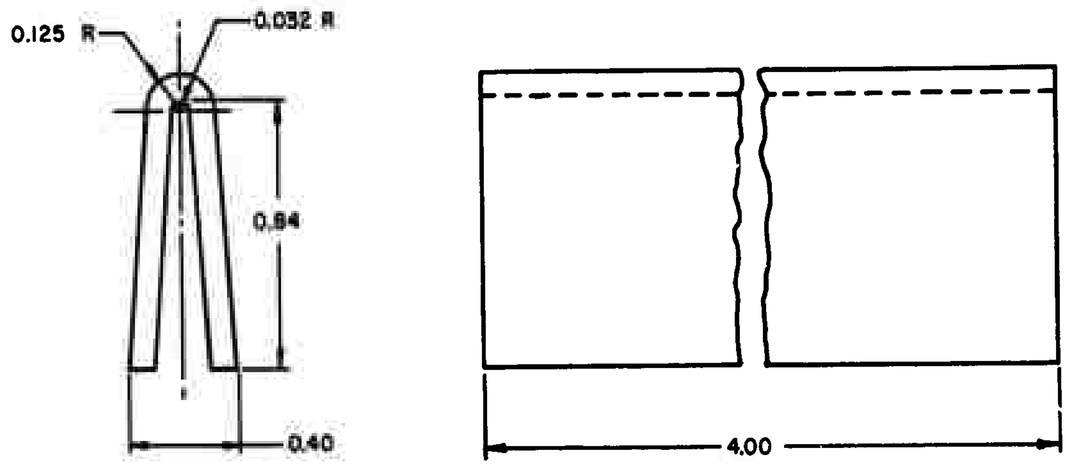


MATERIAL—2024 T-4 ALUMINUM

TOLERANCES — $\pm\frac{1}{64}$ EXCEPT AS NOTED

SCALE FULL SIZE

Figure 9. Aluminum Subsonic Rain Erosion Specimen (1/8" Leading Edge Radius)

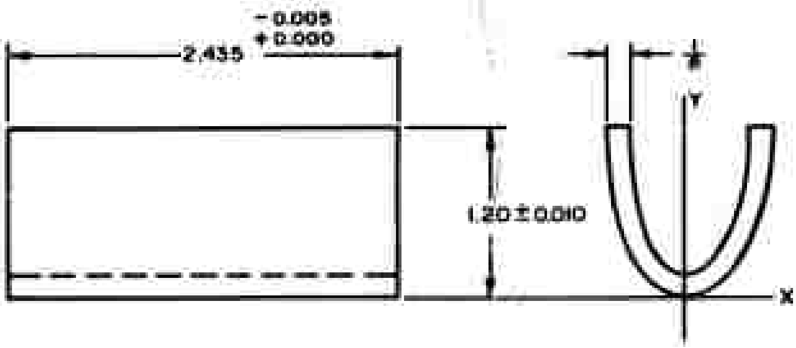


(SCALE – TWICE SIZE)

MATERIAL: LAMINATE — 11 PLIES

TOLERANCES
.XX ± 0.03
.XXX ± 0.010

Figure 10. Laminate ˜ ›sonic Rain Erosion Specimen (3/32" Leading Edge Radius)



.0025 Airfoil-4-Inch Chord

Distance From Leading Edge

%Chord	Ordinate (Y)	Abscissa (X)
.00	.00	.000
1.25	.05	.158
2.50	.10	.218
5.00	.20	.296
7.50	.30	.350
10.00	.40	.390
15.00	.60	.446
20.00	.80	.478
25.00	1.00	.485
30.00	1.20	.500

Outer Dimensions of 1/8 Inch Specimen

Dimensions in Inches

Materials-2024-T4 Aluminum
Resin-Reinforced Laminate

Figure 11. Conformal Aluminum or Laminate Subsonic Rain Erosion Specimen

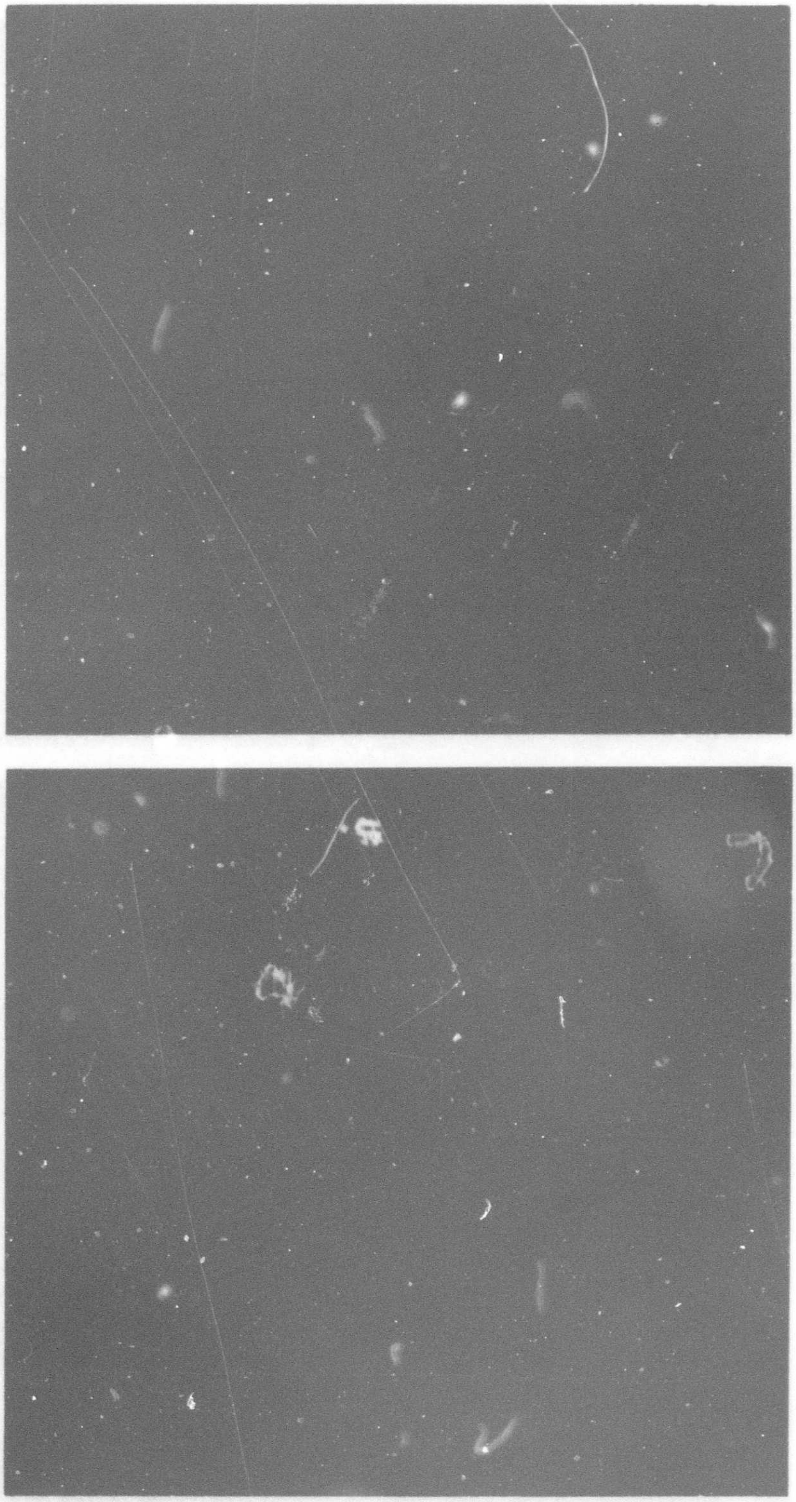


Figure 12. Effect of Needle Size on Drop Size (15- and 18-Gauge Needles)

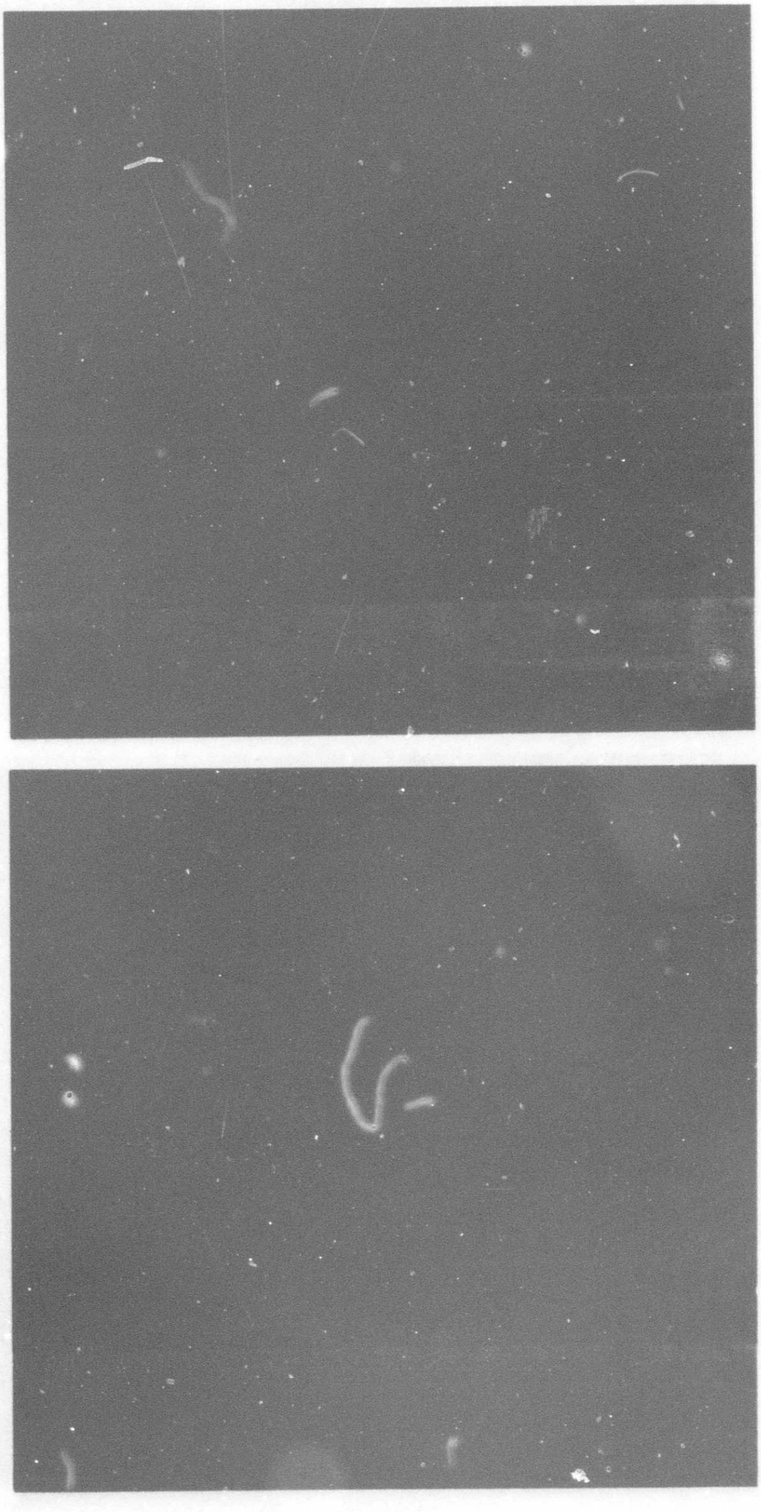


Figure 13. Effect of Needle Size on Drop Size (19- and 20-Gauge Needles)

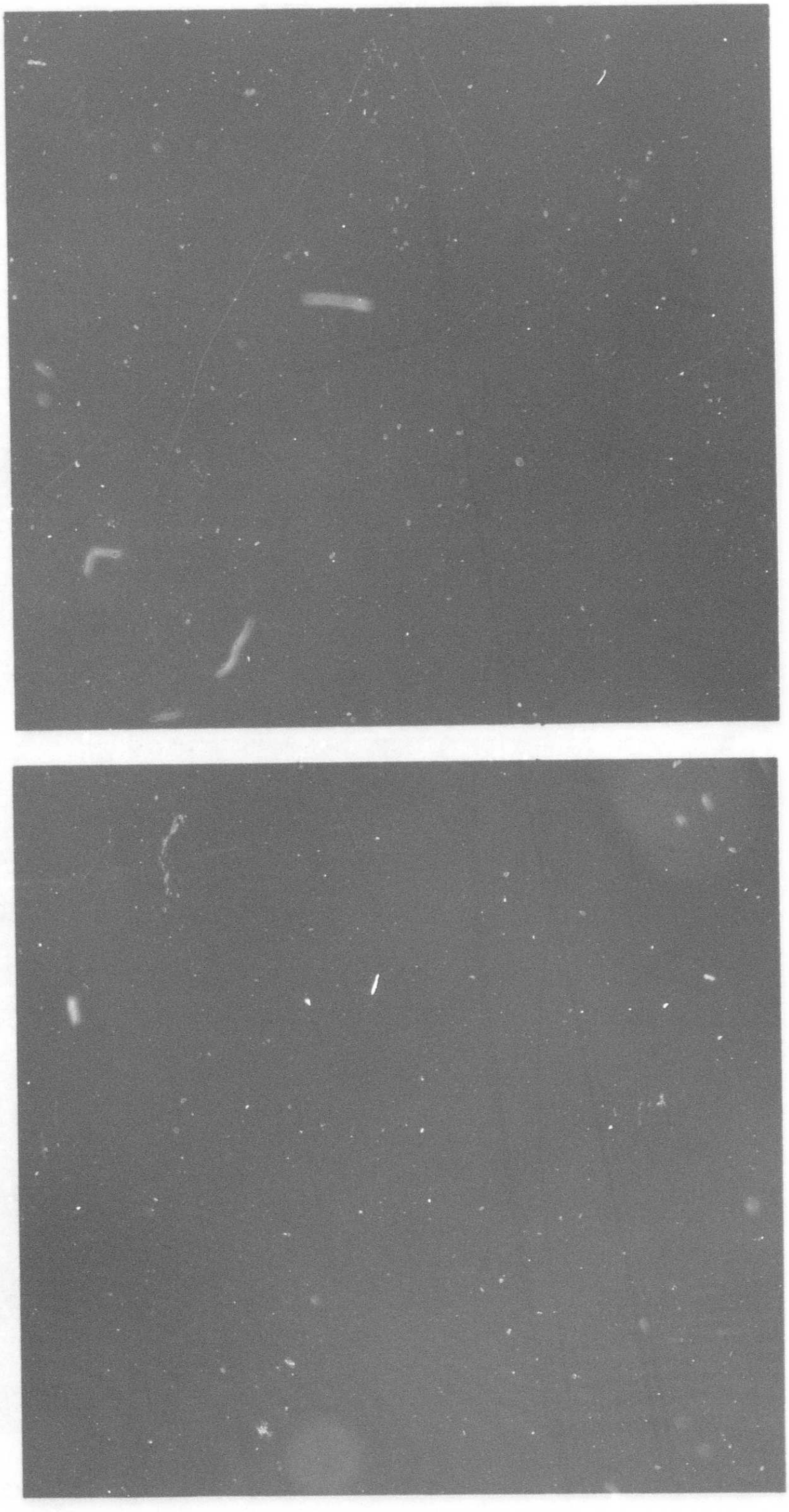


Figure 14. Effect of Pressure on Drop Size (5 and 20 PSI)

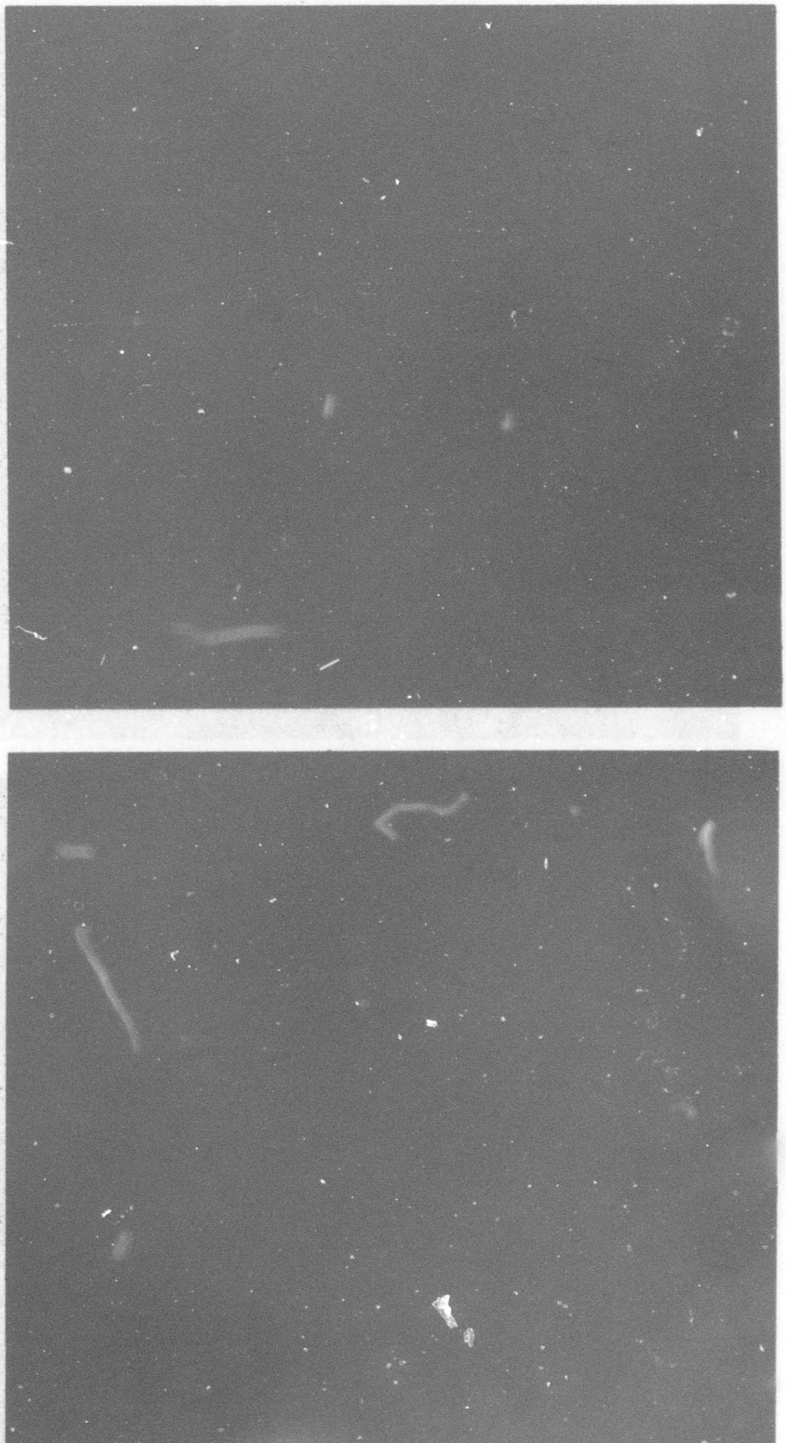


Figure 15. Effect of Needle Size and Pressure on Drop Size (15- and 22-Gauge Needles)

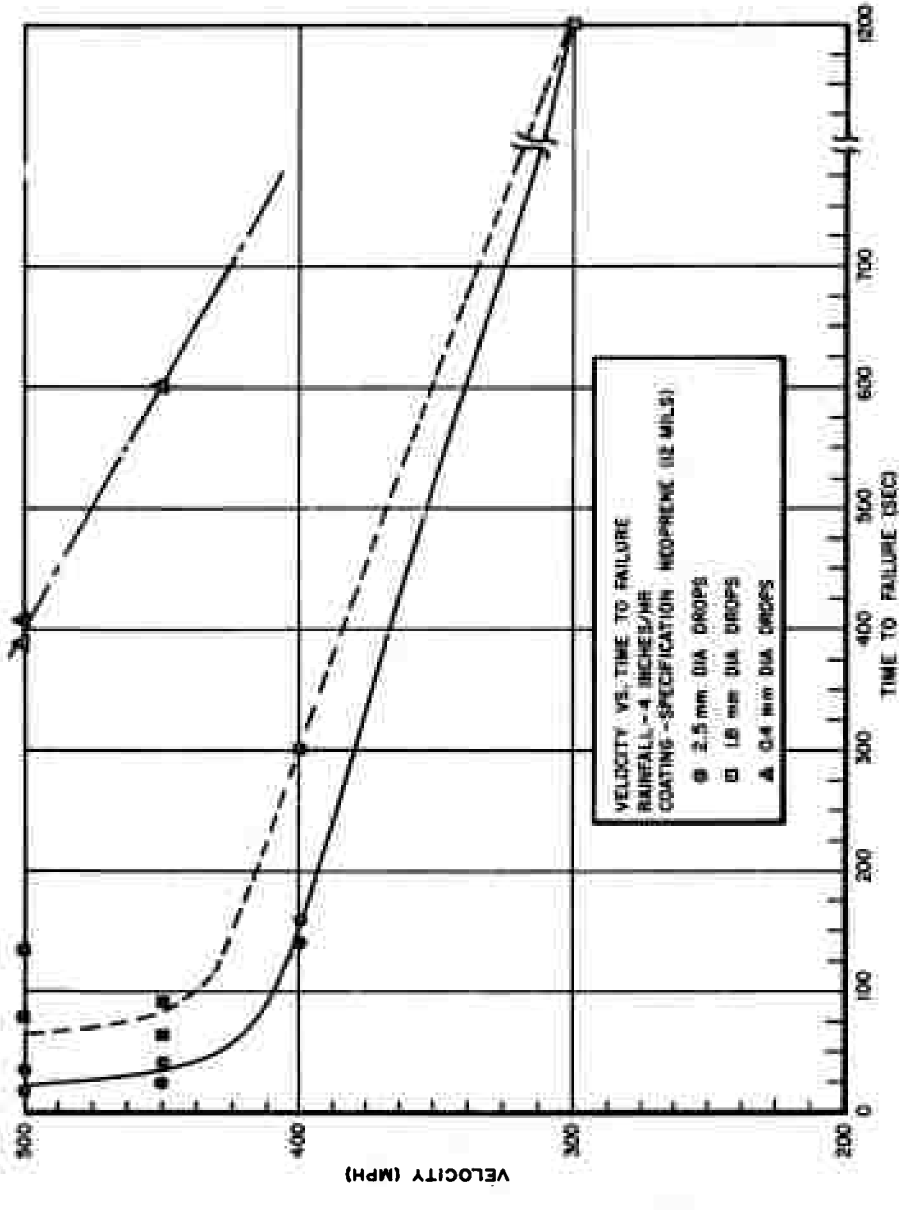


Figure 16. Effect of Velocity on Erosion of Neoprene Coatings (4 inches/hour Rainfall)

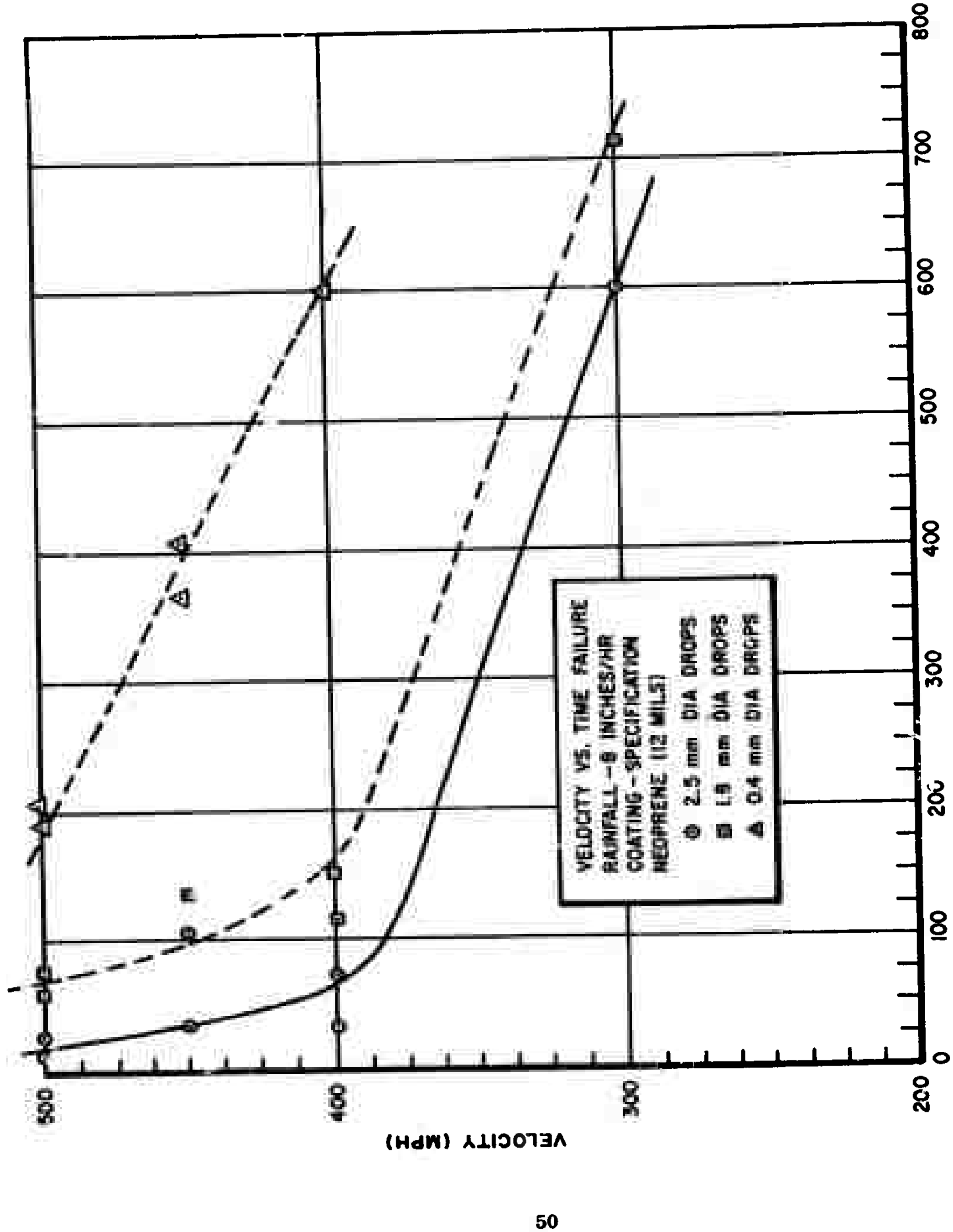


Figure 17. Effect of Velocity on Erosion of Neoprene Coatings (8 inches/hour Rainfall)

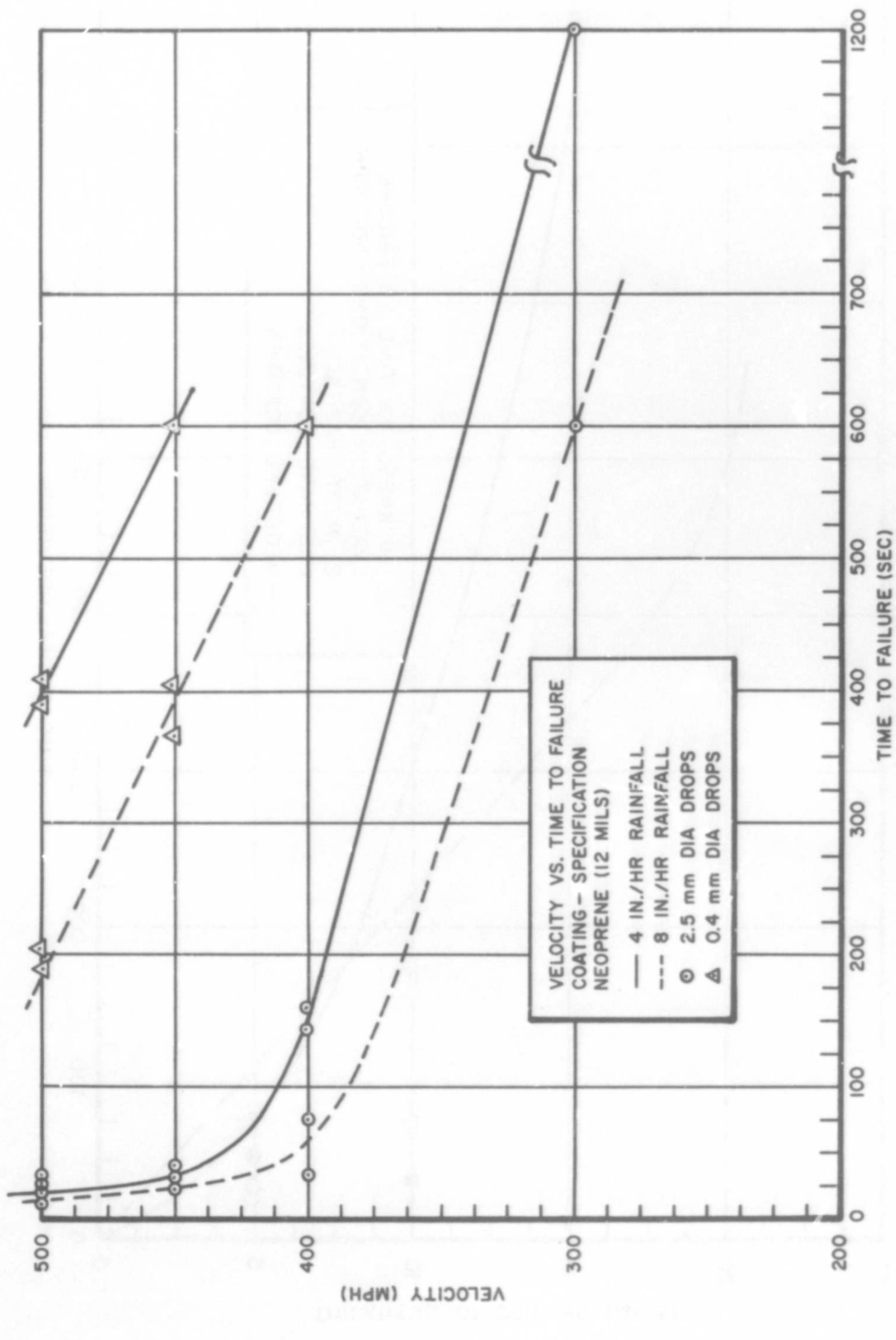


Figure 18. Effect of Rainfall Rate on Erosion of Neoprene Coatings

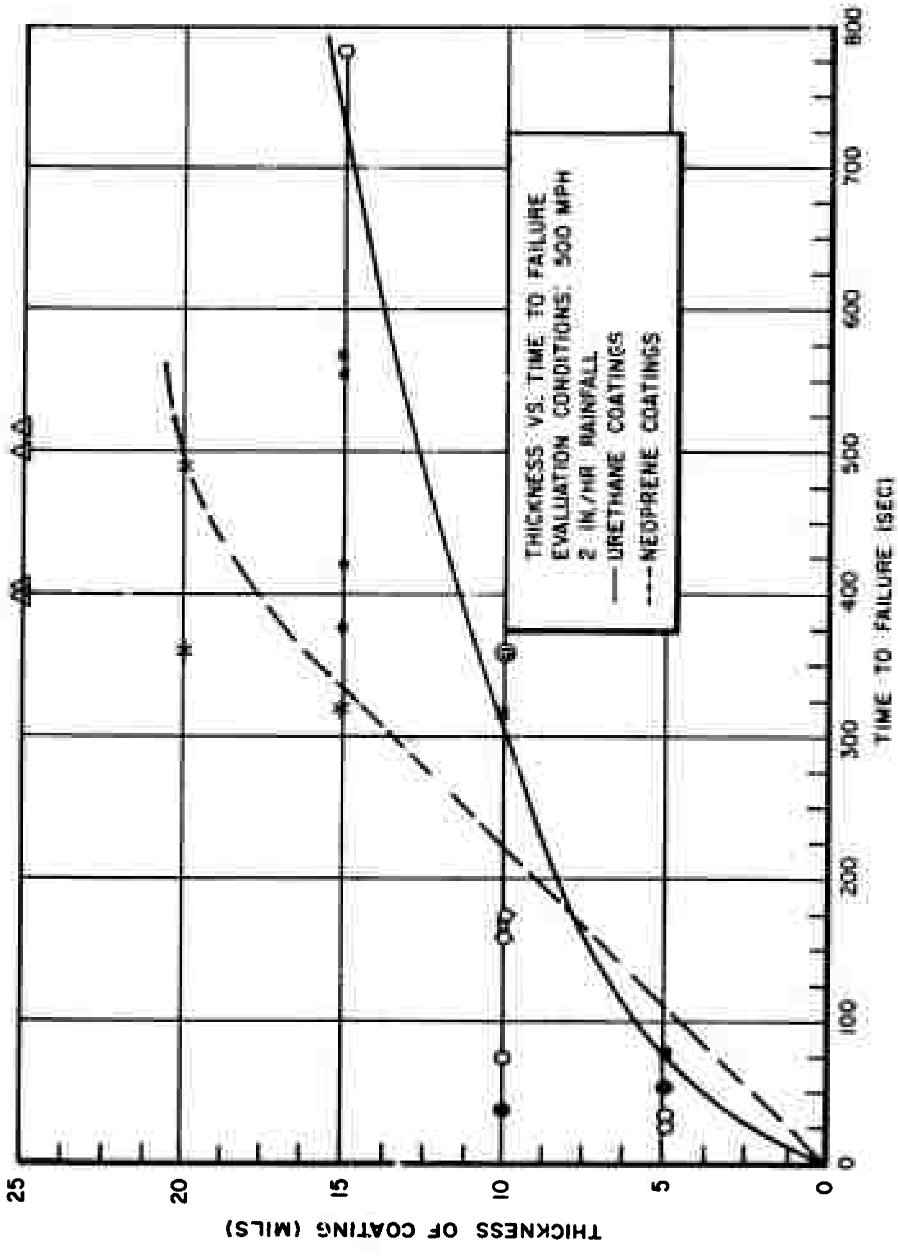


Figure 19. Erosion Thickness Dependence of Urethane and Neoprene Coatings

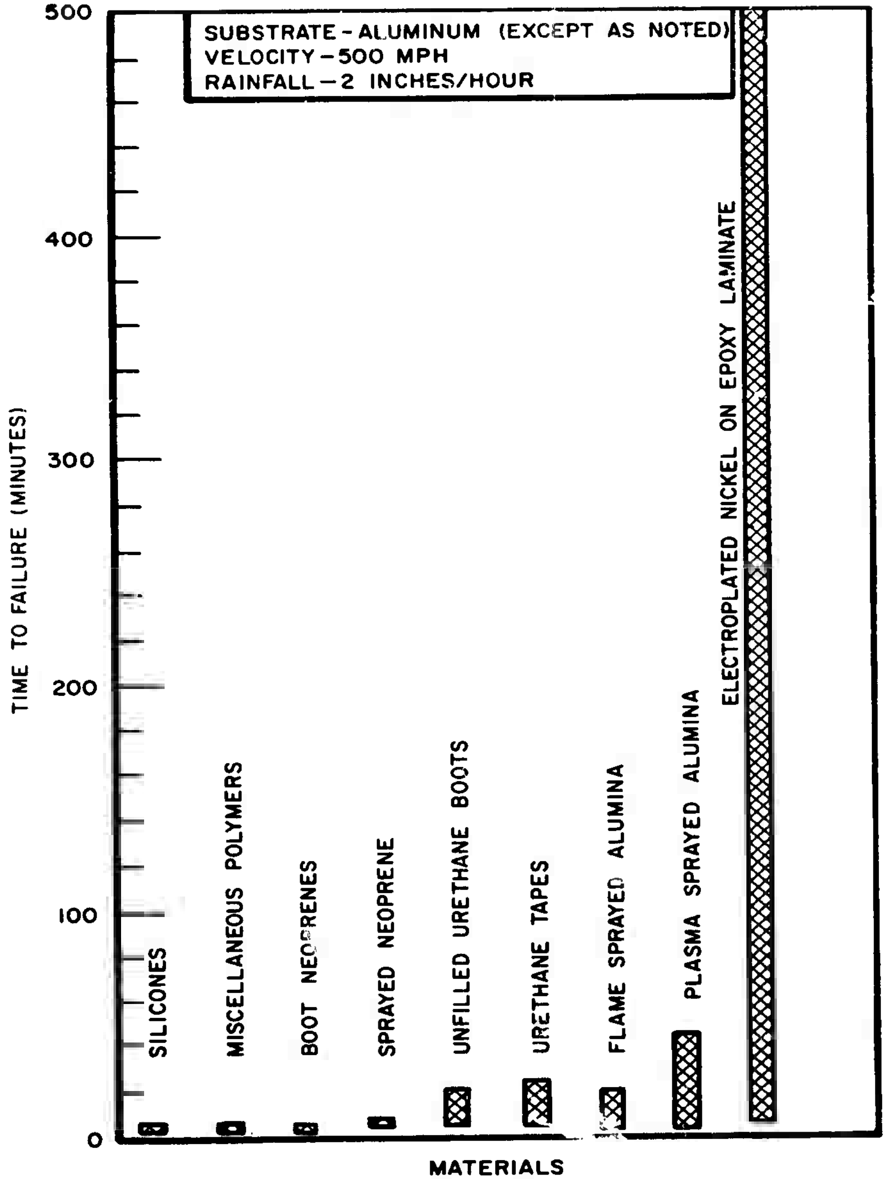


Figure 20. Comparative Erosion Resistance of Materials (Applied as Coatings up to 35 mils Thick)

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13. ABSTRACT

Investigations of advanced coatings materials performed on a whirling-arm rain erosion simulation device at 500 MPH have led to new protective coatings which are capable of providing protection against damage from rain droplet impingement at subsonic velocities. Polyurethane coatings were determined to be the most erosion resistant of the elastomeric-polymeric materials currently available. These polyurethanes are a considerable improvement over the specification neoprene erosion coating. Plasma-sprayed ceramic coatings of alumina and alumina/titania are potentially applicable for supersonic erosion protection where dielectric properties must be maintained. Electroplated nickel coatings directly applied to plastic laminates will provide several orders of magnitude improvement in erosion resistance over conventional elastomeric coatings.

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KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Rain erosion Subsonic Polyurethane Coatings Plasma Sprayed Alumina Coatings Electroplated Nickel Coatings						

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